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Final Project:

Level sensing system

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Year: 2010 - 2011

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Abstract

This report is to present the design and development of a liquid level sensing system based on SCADA system. It is a synthesis of the actions carried out for the construction of the liquid level measuring system. It is structured in five chapters that explain the steps for the realisation of the project.

Knowing the content level of liquid in tanks is very important in industry, although accuracy demands vary according to business requirements. Therefore, it becomes extremely important to monitor and control the level of tanks, vessels, reservoirs, etc.

In this project a liquid tank is analysed with a pressure sensor, and is monitored with the aid of a PLC and a SCADA software.

Acknowledgements

I owe a great many thanks to the people who helped and supported me during the realisation of this project. I would like to dedicate this dissertation to them.

Firstly, I want to dedicate it to my parents, who have always supported me both personal and academically, and who have always encouraged me to continue studying. Besides, I want to dedicate it to my sister, to encourage her to go to the university too.

Secondly, I want to dedicate it to Reg Holme, my project supervisor, for sharing his valuable time and giving me helpful information to finish the project.

Finally, I would also like to thank the Erasmus programme and Glyndwr University for giving me the opportunity to study and live in a foreign country, which has become one of the best experiences in my life.

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1. Introduction

1.1 Background

This project consists in monitoring depth in a vertical water pipe (Fig. 1.1) in the Avionics with Instrumentation & Control laboratory (E12). For that purpose, it has been used a submersible sensor within the pipe, which in the real world it would be suitable for use in rivers, reservoirs, tanks, boreholes, vessels or channels. The sensor was provided by the university, and once the project worked, another of the objectives was to design and build a new depth sensor.

The sensor is connected to a PLC, which can be seen as a little industrial computer highly specialized in getting some inputs, reading its control program, and with some mathematic calculus controlling some outputs. With the use of a SCADA (Supervisory Control and Data Acquisition) the data is sent to a PC which allows an operator to manage and control it.

Fig. 1.1 Vertical water pipes in the E12

1.2 Aim

The intention of this project was to monitor the level in a water pipe with the use of a submersible depth sensor. Once it worked, a new depth sensor was built. The sensor data is sent to a PC, using a SCADA system which connects the PLC to the computer.

1.3 Objectives

In order to achieve the aim, a set of objectives have been planned as follows:

- Research about fluids.
- Study pressure.
- Research on level sensors and pressure measuring.
- Research on principles of control engineering and apply them to the project.
- Design a program for a PLC (Programmable Logic Controller).
- Design a SCADA system.
- Monitoring and analysis of the pressure data given by the provided sensor.
- Design and develop a pressure sensor.

1.4 Block diagram

The element to be controlled is the level in the vertical pipe, which is filled with the aid of the water pump. Level is controlled with a depth sensor and the signal it generates is sent to the PLC, which is the brain of the system and will compute the input to obtain height, pressure and volume. The computed data will be sent to a PC and displayed using a SCADA software.

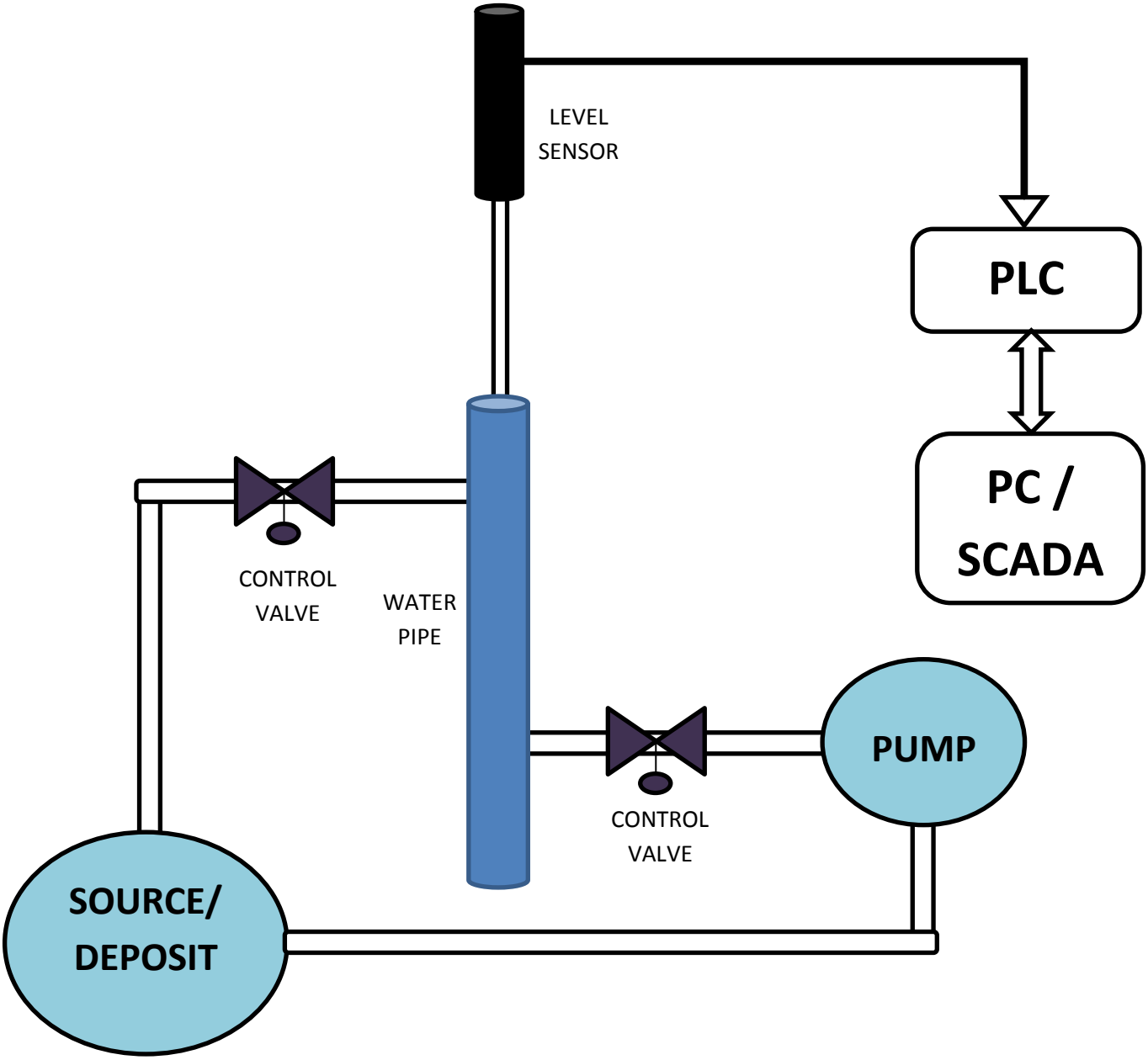
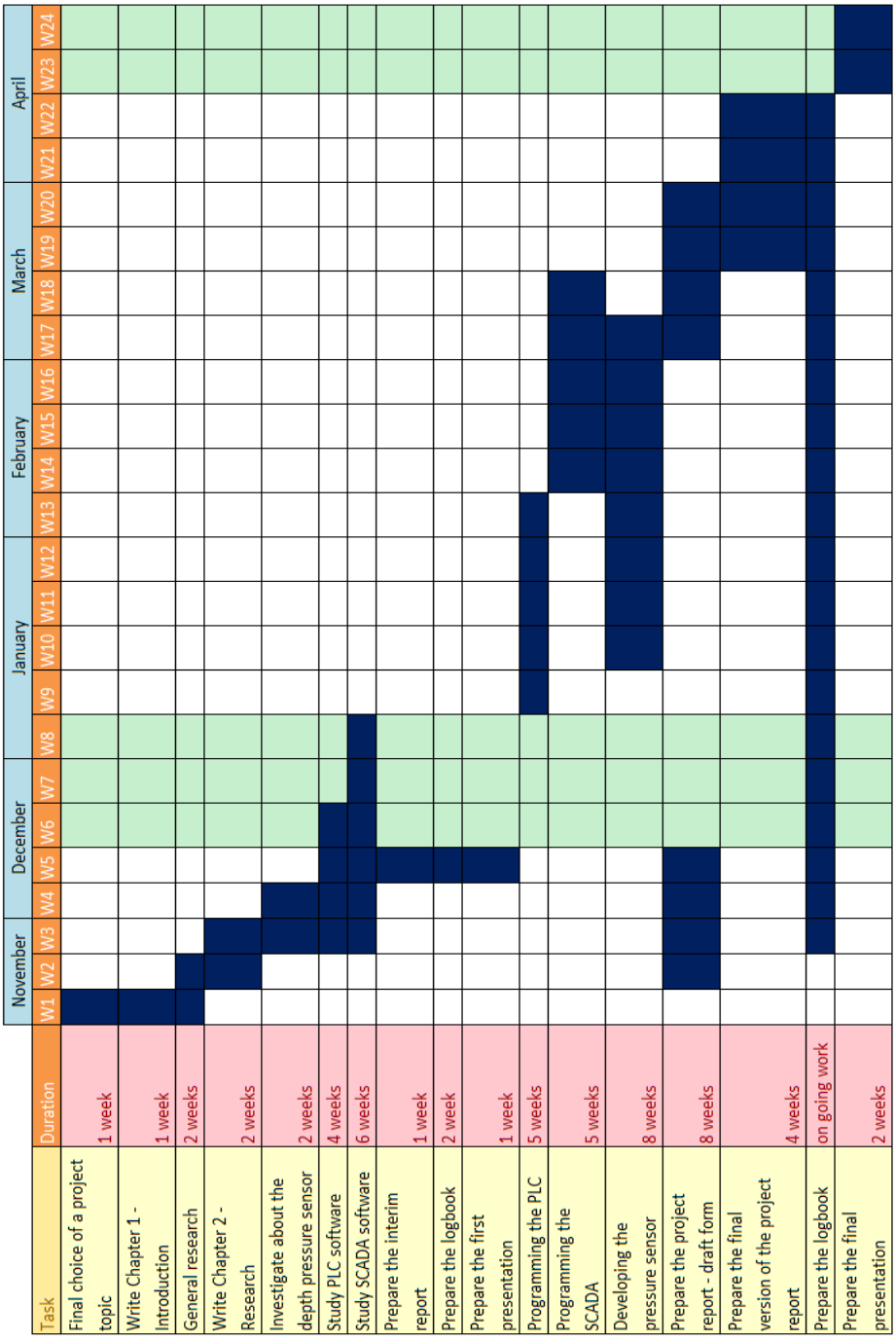


Fig. 1.2 Block diagram of the project

1.5 Gantt chart

The project has two main phases. The first stage will last until Christmas and will include the introduction and research. After Christmas, the programming of the PLC and SCADA as soon as the design and development of the depth sensor will take place. The project report and logbook have to be finished by the end of April.



2. Research

2.1 Fluids

Fluids include liquids and gases. Liquids flow under gravity until they fill the lower zones of the vessel they are in. In a liquid, molecules are joined and they make a force between them which could be compared to the force that join atoms in order to form molecules, so there is an interaction between the molecules like in solids. Molecules in a liquid create short range links transitorily, which are broken due to the kinetic energy in the molecules and then they are formed again. These links are responsible of the liquid union, or else liquid would evaporate immediately as vapour does. The magnitude of this force depends on the molecule [1].

2.1.1 Density

An important property of any substance is the quotient between its mass and its volume, which is called density. Therefore, it is possible to write density as:

$$Density\ (\rho) = \frac{mass\ (m)}{Volume\ (V)} \qquad Equation\ 2.1$$

Where:

- ρ, density, is in kg/m^3
- m, mass, is in kilograms [kg]
- V, volume, is in cubic metres [m^3]

Since the gram is defined as the mass of 1 cm^3 of water, water density is 1 g/cm^3 in the cgs system. If we make the conversion to the International System of Units we obtain that: ρ = 1000 kg/m^3. Precise measurements of density must take into account temperature and pressure, since density in most of materials varies with temperature and pressure changes. The given value of water is for 4°C and 1 atm of pressure. Generally speaking, liquids are essentially incompressible and their variation with pressure is insignificant. For example at room temperature (20 °C), water density changes from 998 kg/m^3 at 1 atm to 1003 kg/m^3 at 100 atm, this is only 0.5%. Density relies more on temperature than on pressure. For example if we fix the pressure at 1 atm, water density changes from 998 kg/cm^3 at 20°C to 975 kg/cm^3 at 75°C, this is a 2.3% so it can also be ignored in most of engineering calculus. This is very well known from the ideal gas law [2].

$$P = \rho RT \qquad Equation\ 2.2$$

Where:

- P, pressure, is in Pascals [Pa]
- ρ, density, is in kg/m^3
- R, mass, is in J / kg · K
- T, temperature, is in Kelvin [K]

Although the cubic meter is the SI unit for volume, the litre (L) is very common especially for liquids and it is defined as 1 L = 1 dm^3 = 10^{-3} m^3. So the density of water is 1 kg/L.

2.2 Measuring the level

Level is defined as a position, line, or flat surface according to which height is measured. Some of the most commonly used liquid-level measurements methods are [3]:

Direct methods:

- Hook indicator
- Glass window
- Float levels

Indirect methods:

- Conduit levels
- Pressure
- Ultrasonic impulses
- Capacitor levels
- Radioactive levels
- Vibrant sheets levels
- Piezoelectric levels

Before taking the decision of which is right for the intended application, some different type of level measuring devices will be studied.

2.2.1 Magnetic, lateral and bulb buoys

The main characteristics are that it is easy to install, operation and calibration are not affected by foam, gases, vapours or variations in the fluid characteristics like dielectric constants or conductivity. It is ideal when a trusted and cheap solution is wanted [3].

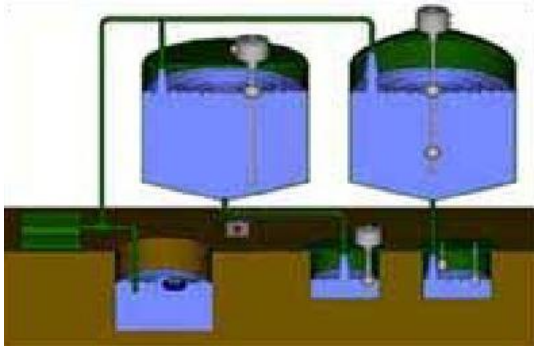


Fig.2.1 Magnetic buoy [3]

The measurement is started either by a pushbutton or a timer. The float is connected to a cable at rest over the liquid. The magnitude which is actually sensed is the variation of the cable tension. The level indication is provided by an electrical circuit associated to the engine which pulls up and down the cable [4].

2.2.2 Conduit sensor

They are mainly used in applications involving control/detection of conduit liquid levels in tanks, deposits or profound shafts. Easy to install and without mobile parts, so there is no need of constant maintenance. There are two versions: rigid or flexible [3].

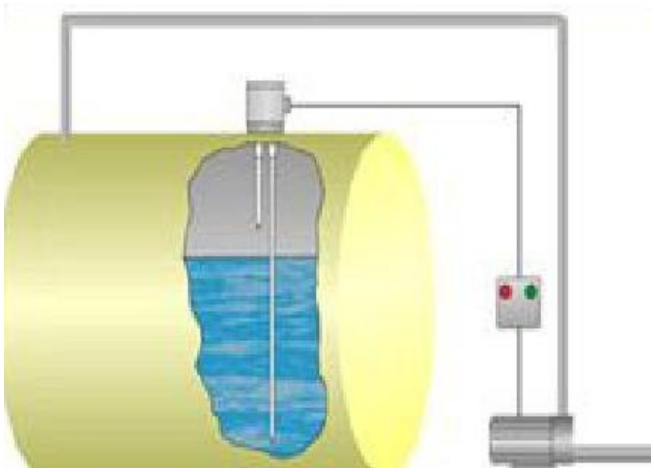


Fig. 2.2 Conduit sensor [3]

It is a very popular method which actually uses the pressure difference transmitter. It sends an electrical or pneumatic signal proportional to the difference of the two liquids, one due to the object liquid level and the other due to a reference pressure, for example, atmospheric pressure [4].

2.2.3 Hydrostatic

They are used in applications where continuous monitoring of liquid level is necessary. There are no mobile parts and they are not affected by turbulences, foam, gases/vapours or fluid characteristics variations like dielectrical constant or conductivity. There are two models: pendulum and lateral [3].

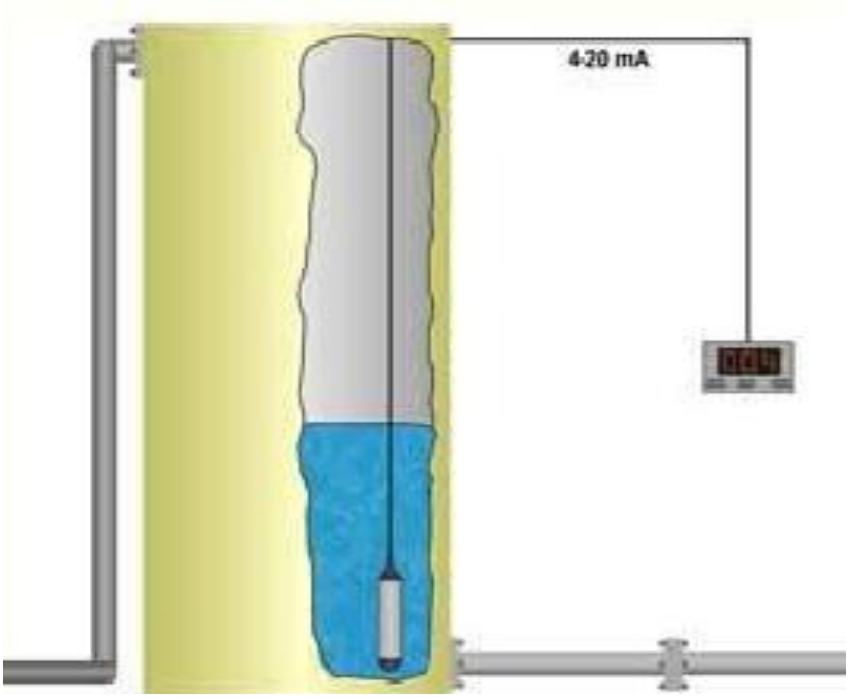


Fig. 2.3 Hydrostatic sensors [3]

With a very similar principle of the conduit sensor, it senses the pressure in the bottom of the vessel, and as it has another pressure input at the end of the cable which is measuring atmospheric pressure, it sends a signal proportional to the pressure difference [4].

2.2.4 Ultrasonic

They give excellent precision and quality, and there is no physical contact between the sensor and the measured media. It allows its use in critical applications like tanks of little diameter or with gases/vapours or powders, although they are sensitive to foams. They can be used with a wide range of materials like water, inflammable and corrosive liquids and granulated solids like lime, concrete, flour or sawdust [3].

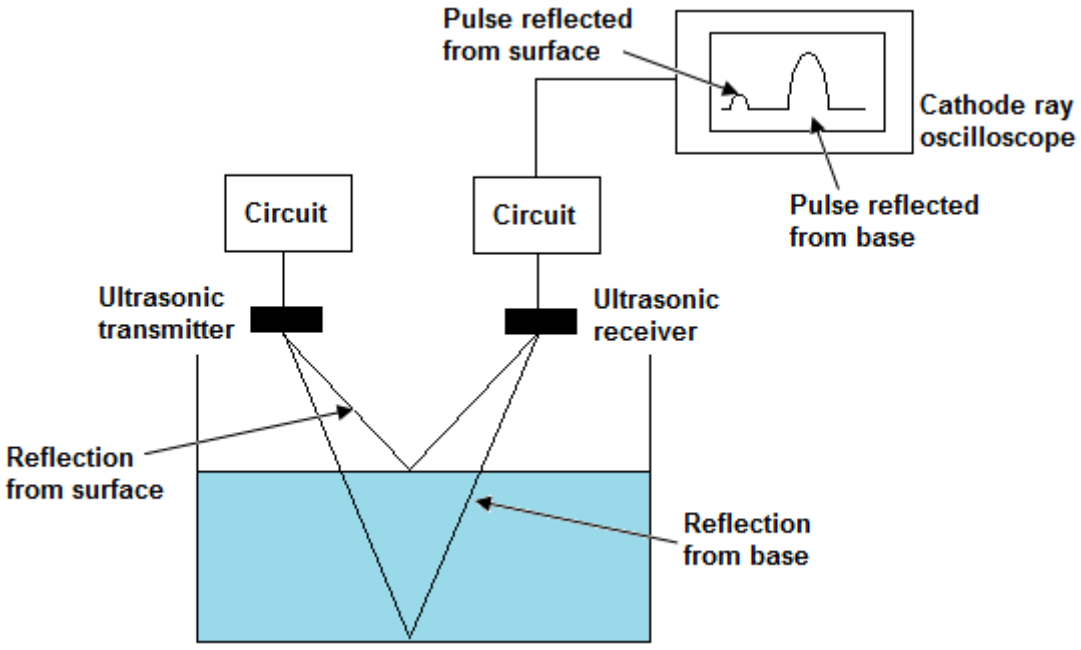


Fig. 2.4 Ultrasonic sensors [3]

There is a hydra-wave transmitter which generates a high-frequency wave (20-40 KHz) which propagates through the gas until it collides with the liquid. Then it reflects and reaches the receiver, located in the same place as the transmitter. The time between transmission and receipt is inversely proportional to the level. As propagation depends on temperature, time will have to be corrected for very accurate measurements. It is essentially a radar method [4]. Advantages are that it has no moving parts hence no wear and tear; it is a non-contact technology and it is easy to calibrate. Disadvantages are that it is affected by powders, heavy vapours, surface turbulence and foam; it cannot operate in vacuum or high pressure; and it needs good reflective surface.

2.2.5 Capacitive level sensor

They have no mobile parts and due to its operation principle (RHF – Radio High Frequency) they are extremely multipurpose with the possibility to be used with products like conductive, viscous or aggressive liquids, apart from granulated materials or powders. They are available for critical temperature conditions and for heavy applications like mining among others [3].

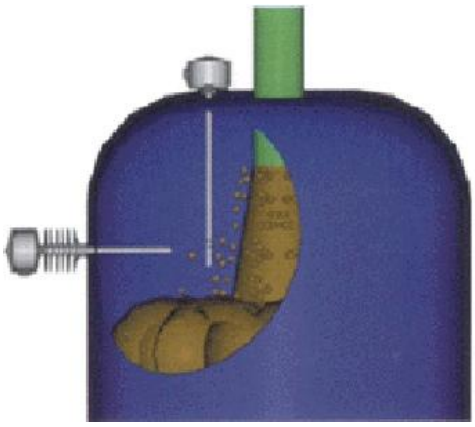


Fig. 2.5 Capacitive sensor [3]

The principle of operation is based on the measurement of the variation of the capacitance of the dielectric media between the metallic sensor and the deposit, or between two sensors in case the deposit is not metallic [4]. Advantages are that it can operate under extreme temperature and pressure, it works with all types of materials and it is typically inexpensive. Disadvantages are that there are intrusive measurements, there are errors due to build-up and varying dielectric strength and it is sensitive to certain applications.

2.2.6 Radioactive level sensor

Radioactive devices can also be used for both discrete and continuous level measurements. They are used when there is no possibility of installing something inside the vessel like in high temperature processes or very corrosive materials. The radioactive source and the receiver are placed in each side of the vessel, when the material is between them the radiation received changes proportionally [4].

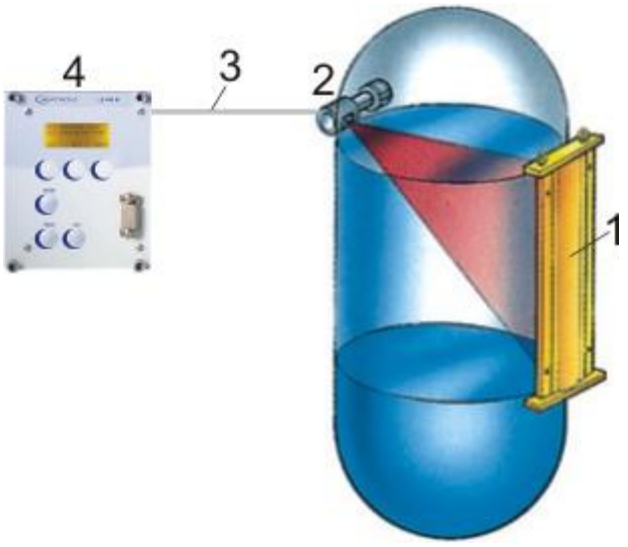
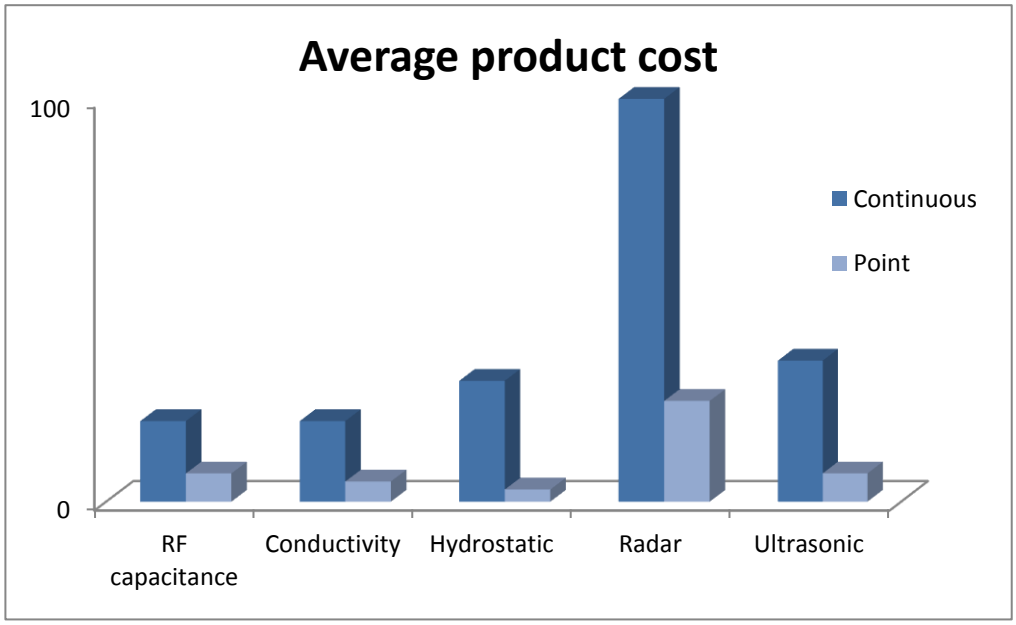


Fig. 2.6 Radioactive sensor [4]

2.2.7 Selecting the best method

The decision is basically made due to the initial cost and the suitability of a certain technique for a given application. However, the decision should considerate that a low initial cost may be accompanied by high maintenance costs or loss of accuracy over time. Suppliers often provide recommendations based on process material, material characteristics, process information, vessel function or power requirements [6].

	Level measurement technologies				
Seven considerations	**RF capacitance**	**Conductivity**	**Hydrostatic**	**Radar**	**Ultrasonic**
Point measurement	■	■	■		■
Continuous measurement	■		■	■	■
Non-conductive liquids	■		■	■	■



The final decision has been to use a hydrostatic head. Firstly, because the sensor provided by the university was of this type and the intention was to develop a similar sensor. Secondly, because it is the cheapest and it has the easiest working principle. So this method which uses pressure is going to be further studied now.

2.3 Pressure

2.3.1 General definition

The pressure is defined as the normal force of a fluid per unit area. Pressure is only for fluids, while its equivalent for solids is normal stress. So mathematically it is written [1]:

$$\text{Pressure (P)} = \frac{\text{Force (F)}}{\text{Area (A)}} \qquad Equation\ 2.3$$

Where everything is in SI units, therefore:

- F is in Newtons [N]
- Area is in squared metres [m^2]
- Pressure is in Pascals [Pa = N/m^2]

2.3.2 Units

As it has already been shown, the SI unit for pressure is the Pascal (Pa), but it is very small for pressures which usually appear in real problems. Therefore, the kilopascal 1 KPa = 103 Pa and the megapascal 1 MPa = 106 Pa are more used [2].

Other units which are very used include:

1 atm = 101.325 KPa = 1.01325 bars = 760 mmHg at 0°C = 1.03323 kg(f)/cm^2 = 14.696 psi = 14.696 lb(f)/in^2

2.3.3 Types

It is possible to define a few types of pressure depending on the reference value of zero [2].

- **Absolute pressure** refers to real pressure, which is measured referenced against a perfect vacuum. In an ideal vacuum the measure would be zero.
- **Differential or relative pressure** is the difference in pressure between two points.

Atmospheric pressure, which is necessary to define the next type of pressure, is the pressure exerted by the weight of air above Earth's surface. It changes under pressure and temperature [2].

- **Manometric or gauge pressure** is a particular case of relative pressure and its reference value is the atmospheric pressure. It is very common for example when measuring the pressure in a car tyre.

$$P_g = P_{abs} - P_{atm} \qquad Equation\ 2.4$$

Now, considering the movement of the fluid two types of pressure will be defined.

- **Static pressure** is uniform in all directions, so measurements are independent of direction.

- **Dynamic pressure** is the pressure exerted by the flow, which applies additional pressure in the perpendicular plane of it.

In this project a static gauge pressure will be measured.

2.3.4 Variation with depth

It is possible to prove that pressure in a static fluid does not change in horizontal planes by doing the balance of forces. However, it does in a vertical plane due to the gravity field. Pressure increases with depth because the deeper you go, the more fluid, and thus the more weight. This “extra weight” in a lower layer is balanced with a pressure increase [1].

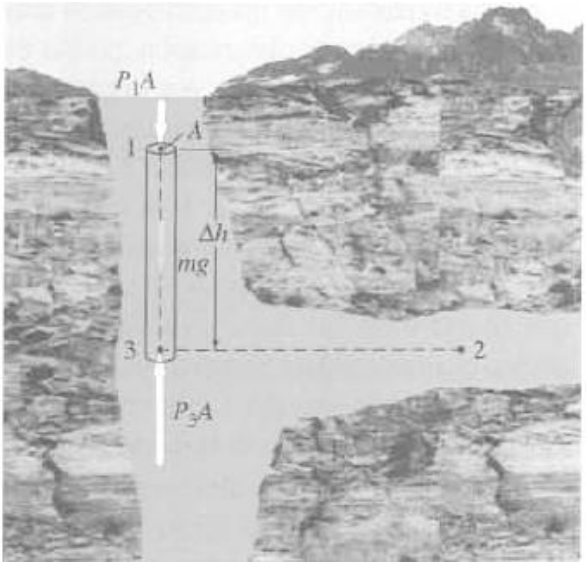


Fig. 2.7 Variation with depth [1]

In order to obtain the relation between pressure (p) and depth (z), an equilibrium fluid of height dy and surface S is considered [8].

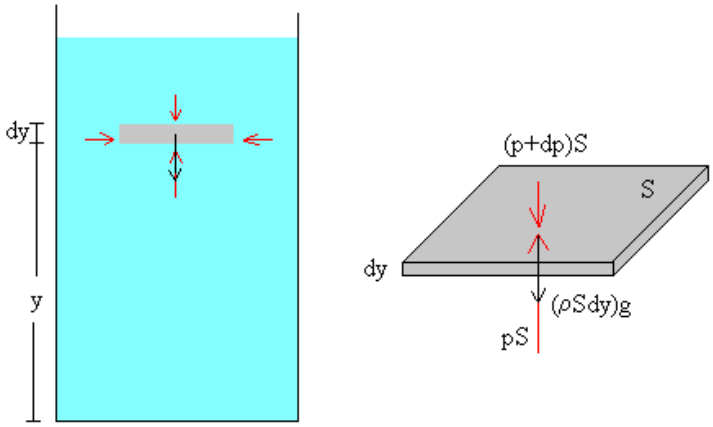


Fig. 2.8 Fundamental law of hydrostatics demonstration [8]

Where:

- y and dy, height and differential of height, are in metres [m]
- p and dp, pressure and differential of pressure, are in Pascals [Pa]
- ρ, density, is in kg/m^3
- S, surface, is in m^2

Given that the density of the fluid (ρ) is constant and provided the gravity (g) is equal to 9.81 m/s^2, the balance of forces in the y axis is as follows:

$$(\rho S \cdot dy)g + pS = (p + dp)S \qquad Equation\ 2.5$$

$$dp = -\rho \cdot g \cdot dy \qquad Equation\ 2.6$$

Now, integrating this equation with the random limits B, A.

$$\Delta p = -\rho \cdot g \cdot \Delta y \qquad Equation\ 2.7$$

Finally, changing the height Δy by depth -Δz, fundamental law of hydrostatics is obtained:

$$\Delta p = \rho \cdot g \cdot \Delta z \qquad Equation\ 2.8$$

Where:

- Δp is in Pascal [Pa]
- ρ, density, is in kg/m^3
- g, gravity, is in m/s^2
- Z, depth, is in m

$$Pa = \frac{kg}{m^3} \cdot \frac{m}{s^2} \cdot m = \frac{N}{m^2} \qquad Equation\ 2.9$$

2.3.5 The hydrostatic paradox

It has already been demonstrated that pressure only depends on depth and it is independent of the vessel shape. However, there may be temptation to think that the pressure is bigger in a vessel in which there is a bigger volume of water [8].

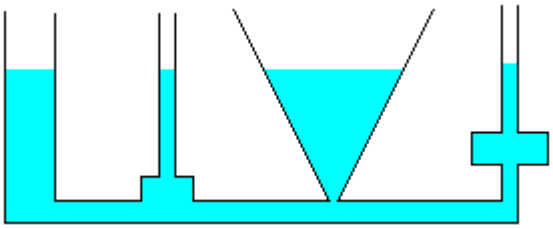


Fig. 2.9 Hydrostatic paradox [8]

The hydrostatic paradox states that the force due to the pressure exerted by a fluid in the base of a vessel can be bigger or smaller than the weight of the liquid that contains the vessel [8]. This means that in each of the vessels, given a fix level, there is a fix pressure value, no matter how the vessel is or the volume of water it has inside.

2.4 Pressure sensors

There are several kinds of instruments to measure pressure: mechanical, pneumatic, electromechanical and electronic sensors.

The principle of operation is as follows:

- **Pressure transducers with deformation meters** work with a diaphragm deviation due to pressure difference between the two chambers. When the diaphragm enlarges due to pressure change, the deformation meter enlarges and a Wheatstone bridge amplifies the signal. A capacitance transducer works with the same principle.

- **Piezoelectric transducers** work based on the principle that an electric potential is generated in a crystalline structure when this is under mechanic pressure. They are faster and more suitable for high pressure applications than diaphragm sensors although they are not as sensitive.

2.4.1 Mechanical pressure meters

The most basic and old of the instruments is the manometer, invented by Torricelli in 1643. It is based on height to measure pressure, according to the principle above. It is a U-shape tube which contains mercury, water, alcohol or oil depending on the expected pressure differences [2], [9].

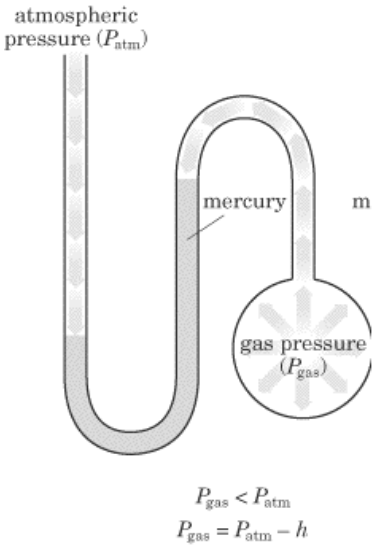


Fig. 2.10 Basic manometer [10]

Another mechanical device to measure pressure is the Bourdon tube, due to its inventor, consisting on a metallic bended hollow tube, like a hook, finishing on an indicating needle. When the tube is open to atmosphere it has no deviation and the needle is calibrated to zero. When it is pressurized, the tube lengthens and the needle moves proportionally to the applied pressure. Other types of Bourbon tubes have different shapes like spiral, helicoidal or twisted [2].

Fig. 2.11 Bourdon tube [11]

The diaphragm sensor consists on a capsule divided by a membrane, one side is open to targeted pressure and the other side is connected to a reference pressure [12].

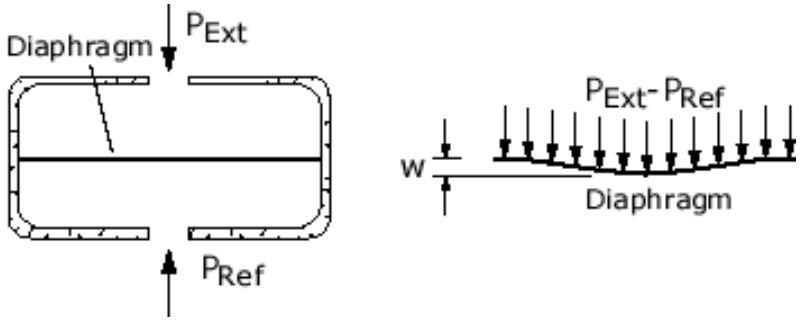


Fig. 2.12 Diaphragm sensor [12]

Therefore, with this kind of devices it is possible to obtain the gauge pressure.

The bellows sensor is similar to the diaphragm but in a single piece flexible axially, which allows a big displacement. They have a great service life, which means they bear millions of flexion cycles without deformation [9].

2.4.2 Pneumatic pressure meters

The pneumatic transmitter instruments are based on the nozzle-plug system. They consist on a pneumatic tube augmented to a constant pressure P, with a nozzle in the end which can be obstructed by a plug, the position of which depends on the output [9].

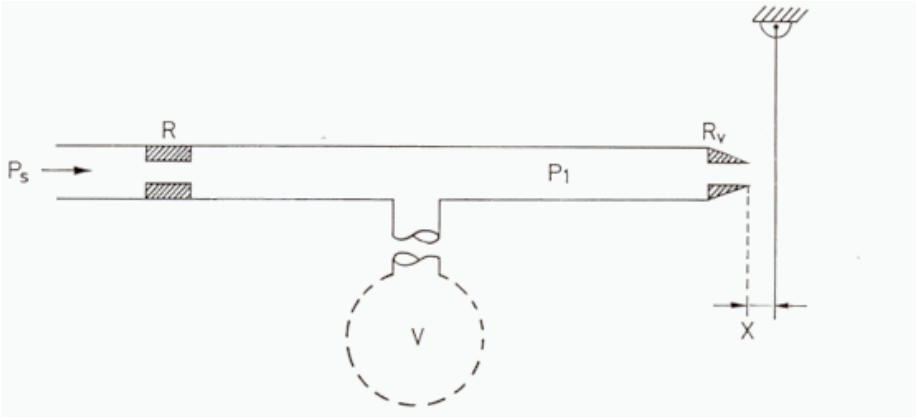


Fig. 2.13 Nozzle-plug system [9]

2.4.3 Electromechanical and electronic pressure meters

Electronics has also changed the pressure measuring. Pressure transducers convert the pressure change to a voltage, magnetic, resistance, inductance or capacitance change. They are lighter, faster, more sensitive, trustworthy and precise that their mechanic equivalents. They also have a great range varying from a millionth of 1 atm to some thousands of atm [2].

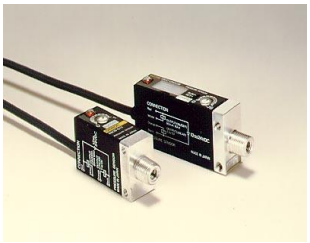


Fig. 2.14 Electronic pressure sensors [9]

- **Manometric pressure transducers** use atmospheric pressure as a reference and they give a zero output signal at atmospheric pressure whichever the altitude is.

- **Absolute pressure transducers** give a zero output value when in vacuum.

- **Differential pressure transducers** measure the difference between two pressure values directly instead of using two pressure transducers and calculating the difference.

2.5 Industrial Control

2.5.1 Introduction to PLCs

PLCs (Programmable Logic Controllers) are solid-state members which use integrated circuits instead of electromechanical devices to control in real time a sequential process in an industrial environment. They produce an output to the information provided by the sensors of the automatized system. They implement control functions, so they are capable of storing instructions, such as sequencing, timing, counting, arithmetic, data manipulation, and communication, to control industrial machines and processes [13], [14].

The idea was born in 1968 when General Motors specified the design criteria for the first PLC to substitute high-cost relay-controlled systems. Their main characteristics are the survivability in industrial environments, ease of program and maintain by engineers and technicians and reusable.

Apart from that, the price had to be competitive with current relay systems, and it had to interact with a central system. By the end of the year the first PLC had been developed. They met the requirements of modularity, ease of install, reduced space, programmability, reusability and capability of use in an industrial environment. The programming was a little tedious but the ladder diagram format standard had been developed. By 1971, the use of PLCs had spread to other industrial sectors.

Nowadays, PLCs have improved in areas like speed of operation, interfaces or data-processing but the main requirements are the same of their predecessors. The improvements are not only in hardware but in software too.

This section is just an introduction to understand what a PLC is since further study and programming of PLCs and will be included in the next chapters.

2.5.2 Introduction to SCADA

SCADA is an acronym for “Supervisory, Control and Data Acquisition”. SCADA get together all the processes in charge of doing the specific functions which have to be done in a general system from the equipment that form a given installation. Then, the data is sent to a central computer to be managed and controlled [14].

HMI environment (Human Machine Interface) is the SCADA interface and must be able of managing the use of the different sources in real time, taking into account the constraints of the different processes which form the system and which force each process to take place within a given interval of time. This tool has to be friendly to the user, which is usually a forgotten part in the automation process.

Summing up, a SCADA system is a joint of devices and programs aimed to control and supervise secure and efficiently an industrial process in real time from an operator post. Its goal is to ease the operation of the control system and must provide the operator real time centralized information, remote control and historical information of the system variables. With this, a better vision of the system is provided and allows easier problem detection and solving. With the obtained data some statistical studies and curves of variables trends may be done.

3. Design

In this chapter, the whole system design will be done. Firstly, a sensor provided by the University will be used as a benchmark to test the software. Then, a new sensor will be designed with the purpose of getting a cheaper solution to the system. This sensor output will be treated in a PLC, which will compute level, pressure and volume. Finally, this data will be monitored on a PC using a SCADA software.

3.1 Sensor

Firstly, the depth sensor used was the one provided by the University, corresponding to the model Pi9911-4mWG-C10 from Applied Measurements LTD.

Fig. 3.1 Depth sensor [15]

This sensor gives an output ranging 4-20 mA, with a range of 4 metres Water Gauge (mWG) and a cable length of 10 metres. It assures a high integrity waterproof assembly which is rated to 200 metres depth. It has an accuracy greater than 0.25% of the pressure range.

It has three wires and a static pressure input coming out from the cable. The sensor connections are as follows:

- Red = Positive Supply
- Blue = Negative Supply
- Green = Earth

The setup would probably be similar to the diagram below so the sensor has a constant power supply that is normally 24vdc. When the sensor changes output the current in milliamps varies between 4 and 20.

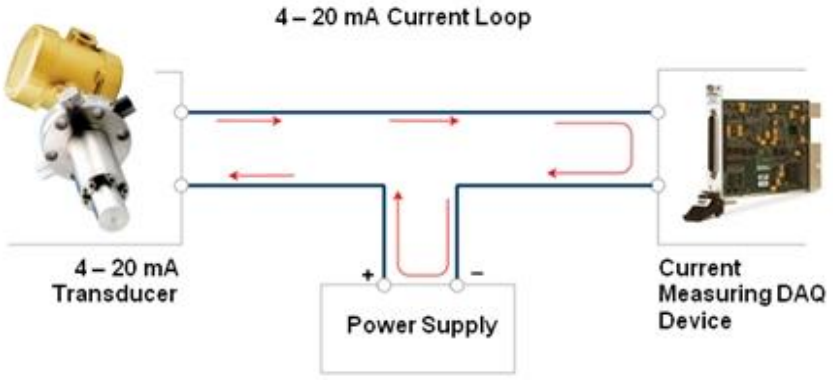


Fig. 3.2 Depth sensor setup [15]

3.1.1 The transducer

One of the main objectives of the project was developing a new depth sensor. In order to do that, a research on pressure transducers was carried out. The decision was to use the piezoresistive silicon pressure sensor SSCSANN005PGAA3 from Honeywell [16].

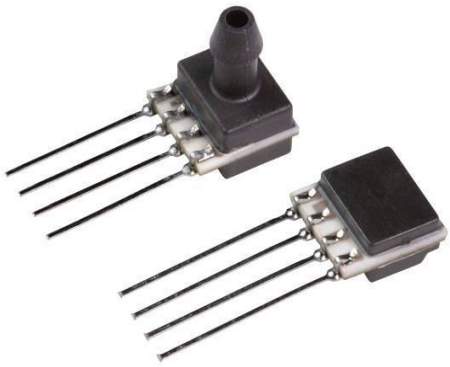


Fig. 3.3 Pressure transducer [16]

This code shows:

- SSC = Series
- S = SIP (Single Inline Package)
- AN = Pressure Port: Axial, single port
- N= No diagnostics
- 005PG = Pressure Range 0 psi to 5 psi (Gage)
- A = Output type: Analog Voltage

- A = Transfer function: 10 % to 90 % of Vsupply
- 3 = Supply Voltage Range: 3.3V

The transfer function for this sensor with "A" calibration is the following:

$$Output\ (Volts) = \frac{0.8 \cdot V_{supply}}{P_{max} - P_{min}} \cdot \left(P_{applied} - P_{min}\right) + 0.10 \cdot V_{supply} \qquad Equation\ 3.1$$

Since pressure depends lineary on height, it is possible to transform the equation to the one below:

$$Output\ (Volts) = \frac{0.8 \cdot V_{supply}}{h_{max} - h_{min}} \cdot (h_{actual} - h_{min}) + 0.10 \cdot V_{supply} \qquad Equation\ 3.2$$

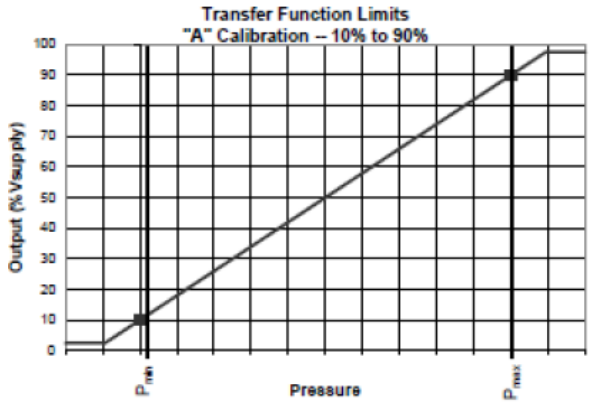


Fig. 3.4 Sensor transfer function [16]

Knowing that the vertical water pipe is 3.2m of height, it is possible to calculate the maximum pressure that will be applied.

$$P_{max} = \rho \cdot g \cdot h_{max}$$

$$P_{max} = 1000\ \frac{kg}{m^3} \cdot 9.81\ \frac{m}{s^2} \cdot 3.2\ m = 31.392\ KPa \cdot \frac{1\ psi}{6.8948\ KPa} = 4.553\ psi$$

Now, it is known that pressure values will vary from 0 psi – 4.553 psi. Therefore, the output voltage values will be:

$$Output_{max}\ (Volts) = \frac{0.8 \cdot 3.3V}{5\ psi} \cdot (4.553\ psi) + 0.10 \cdot 3.3\ V = 2.734\ V$$

$$Output_{min}\ (Volts) = 0.10 \cdot 3.3\ V = 0.33\ V = 330mV$$

3.1.2 Amplifying the signal

Since the intention was to develop a similar sensor than the one provided by the university, the next step was to amplify the output voltage to a range of 0-10 Vdc. In order to do that, firstly the gain needed was calculated.

$$Av = \frac{10\ V}{2.73\ V} = 3.66$$

Then, a very common circuit to amplify without inverting the signal was used:

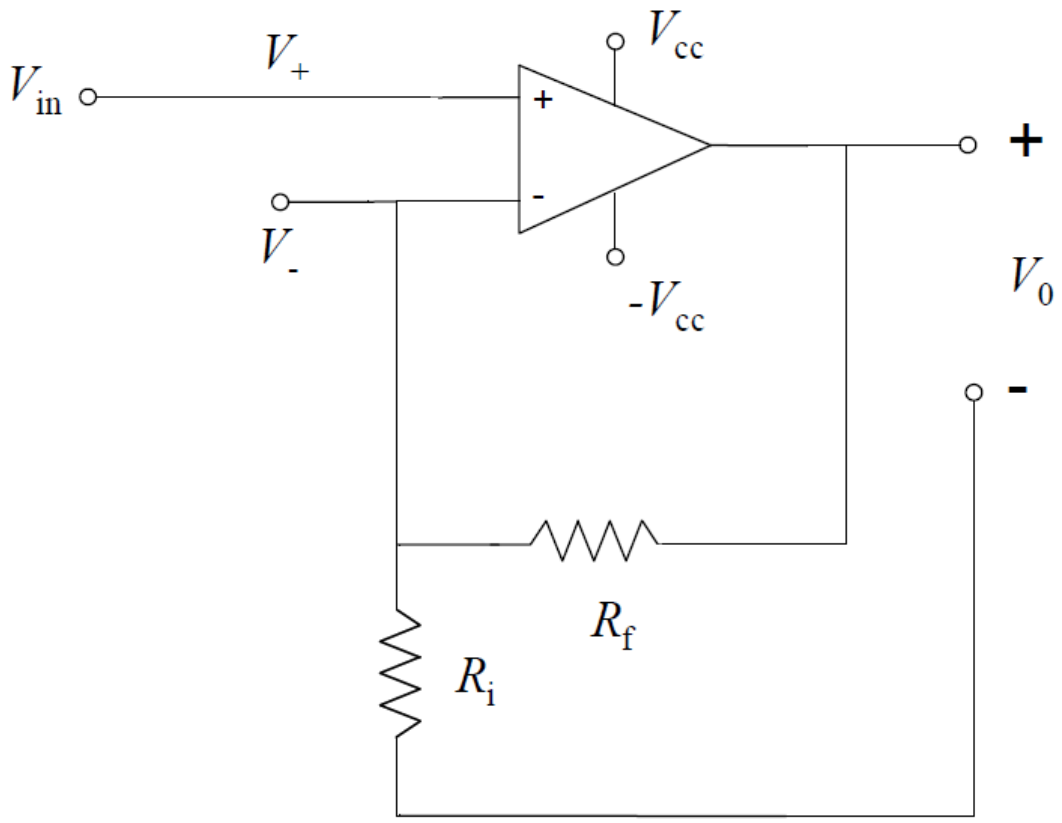


Fig. 3.5 Non-inverting amplifying circuit

The main characteristics of this circuit are:

$$R_{in} \approx \infty$$

$$R_{out} \approx 0$$

$$V_O = \left(1 + \frac{R_f}{R_i}\right) \cdot V_{in} \qquad Equation\ 3.3$$

$$Av = \frac{V_O}{V_{in}} = 1 + \frac{R_f}{R_i} \qquad Equation\ 3.4$$

So, as a gain of 3.66 is needed,

$$Av = 3.66 = 1 + \frac{R_f}{R_i}$$

$$\frac{R_f}{R_i} = 2.66$$

$$R_f = 2.66 \cdot R_i$$

Taking a value of 10 kΩ for Ri, the value obtained for Rf is approximately 25 kΩ.

Now, the output voltage ranges from 1-10V.

The opamp that will be used will be the LM741CN from National Semiconductor, the most important characteristic for us is that the supply voltage is ±18V.

3.1.3 Converting voltage to current

The final step to make the sensor similar to the one provided, would be converting the voltage output ranging 0-10 Vdc to a current ranging 4-20 mA, with 4 mA representing the lowest end of the range and 20 mA the highest. Since the circuit is a few metres far from the sensor, the voltage gets attenuated due to the resistance of the wires. Converting the voltage signal to current using the technique known as the current loop improves the accuracy of the signal, which is not affected by voltage drop in the wiring whatever the electrical resistance in the wiring is.

So, in order to make the conversion, it is possible to use an integrated circuit like the XTR110, a precision voltage-to-current converter designed for analog signal transmission. It accepts inputs of 0 to 10V and can be connected for outputs of 4mA to

20mA. The main problem of these IC's is the price, which ranges from 20 to 100 GBP, and the complexity of its design.

The other possibility is to design a circuit which performs the conversion, in order to do that it is possible to look at the internal circuit of the XTR110:

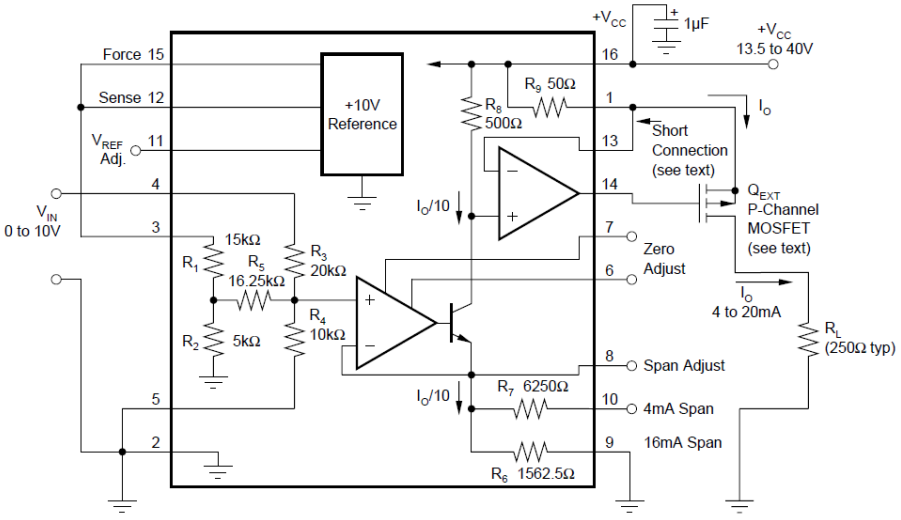


Fig. 3.6 Voltage-to-current converter [17]

The other option is found in textbooks. The voltage to current converters feeding to grounded loads circuit is the following:

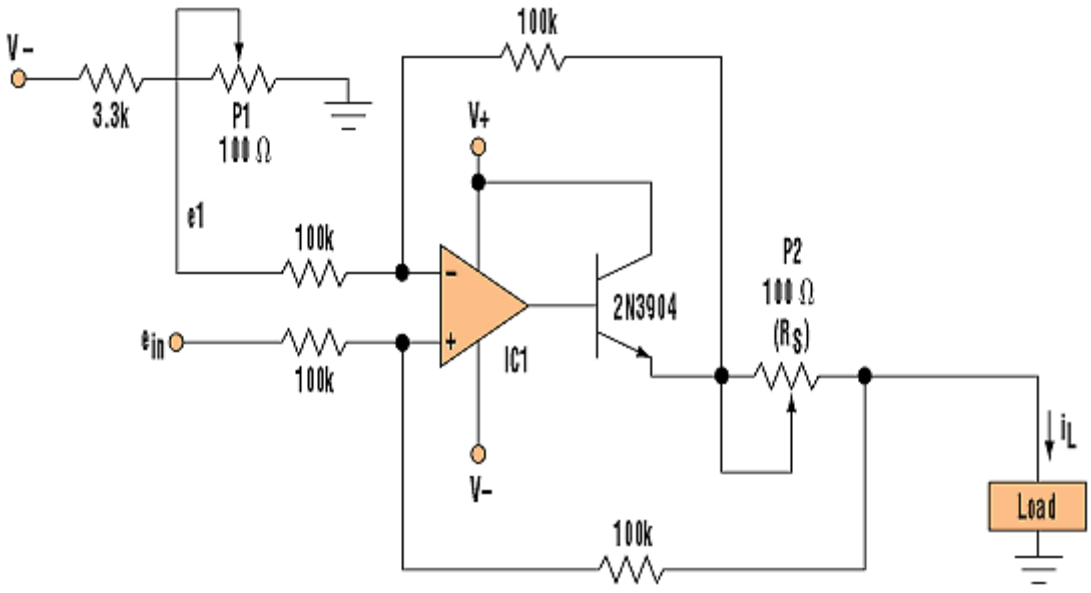


Fig. 3.7 Voltage-to-current converter [18]

This conventional circuit gives 4 to 20 mA of output for an input of 0 to 10 V. First, it is necessary to adjust P1 for zero (4 mA) and then P2 for span (20 mA). The circuit needs a positive and negative supply, which depend on the operational amplifier but typically are ±15V.

Finally, this part was not developed. the reason is related to the resolution of the PLC and will be further studied later. So the sensor developed in this project gives a voltage output ranging 1-10 V depending on the pressure.

3.2 The Programmable Logic Controller (PLC)

The PLC has already been introduced, so now the specific model used in this project will be analysed. It is the SLC 500 with 10 slot rack from Allen-Bradley (AB), which is a chassis-based, modular family of controllers and I/O,

Fig. 3.8 PLC SLC 500

In order to make a PLC work, it is necessary at least one power supply module and one controller (CPU), which is also the communications module. In this case, the power supply module is the 1746-P1 which allows 110/240V input and 2 A of output. Besides, the controller module is the 1747-L532 with the CPU SLC 5/03 which has the following features [19]:

Controller Series	Instruction Memory Words	Max. I/O Points	I/O Options	Built-in Ports	Additional Features
SLC 5/03	8 K, 16 K, or 32 K	4096	Local I/O, remote I/O	DH-485, RS-232-C (ASCII or DF1)	Connects to external intelligent devices using the RS-232 port, without additional modules

Also in this case, the communications will be through the RS232 port, which has a DE-9 pin connector. It is possible to see a photo of the module below.

Fig. 3.9 Communications module 1747-L532

3.2.1 The input module

The input module is the 1746-NI4, which is an analog module containing 4 analog input channels that are user selectable per channel for voltage or current to support a variety of monitoring and controlling applications [20].

Each analog input channel can be configured for either voltage or current. The NI4 has 4 individual DIP switches that control the input mode of input channels 0 through 3. A switch in the ON position configures the channel for current input. A switch in the OFF position configures the channel for voltage input. These switches can be seen in red in the photo below.

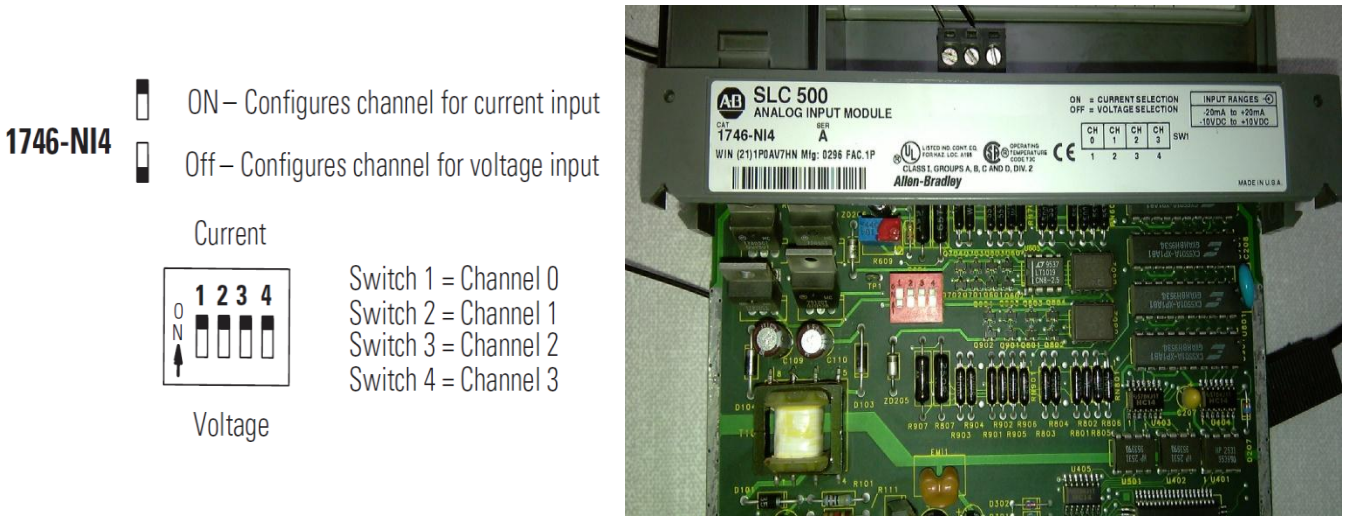


Fig. 3.10 Input module configuration [20]

The wiring of the module would be like this for the voltage wiring:

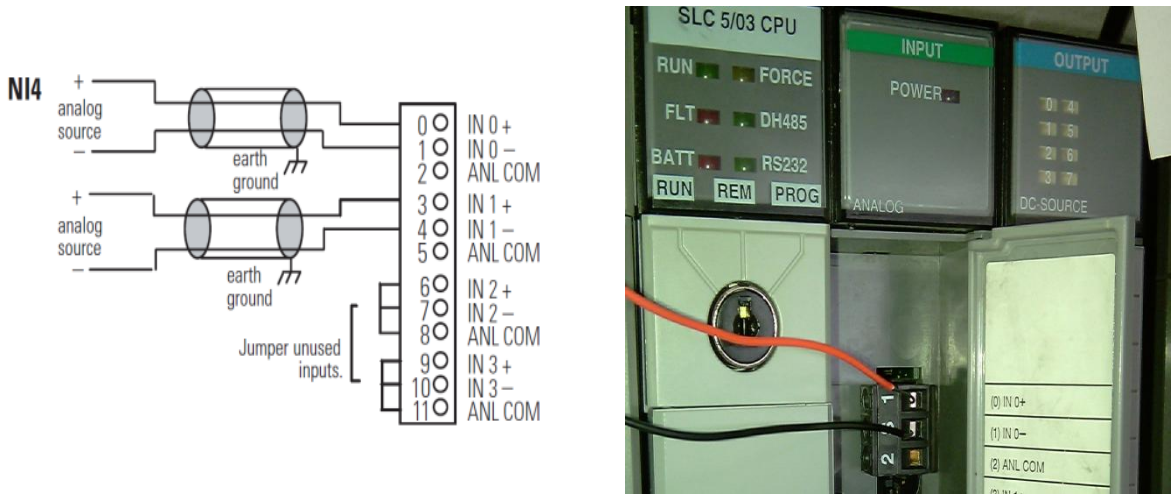


Fig. 3.11 Voltage input module wiring [20]

And since the current sensor has positive and negative supply plus earth wires, the connection would look like this for the current input:

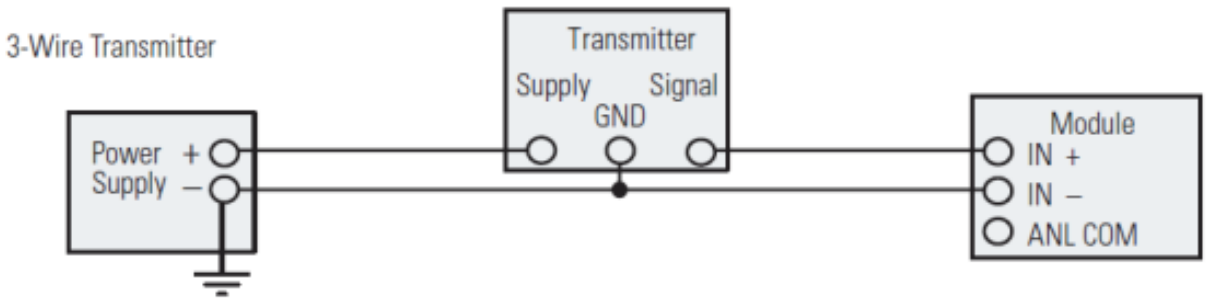


Fig. 3.12 Current input module wiring [20]

The table below identifies the current and voltage input ranges for the input channels, the number of significant bits for the applications using input ranges less than full scale, and their resolution.

Voltage/Current Range	Decimal Representation	Number of Significant Bits	Resolution per LSB
-10V dc to +10V dc - 1LSB	-32,768 to +32,767	16 bits	305.176 µV
0 to 10V dc - 1LSB	0 to 32,767	15 bits	
0 to 5V dc	0 to 16,384	14 bits	
1 to 5V dc	3,277 to 16,384	13.67 bits	
-20 mA to +20 mA	-16,384 to +16,384	15 bits	1.22070 µA
0 to +20 mA	0 to 16,384	14 bits	
4 to +20 mA	3,277 to 16,384	13.67 bits	

Fig. 3.13 Converting analog input data [20]

Therefore, by using 1-10 Vdc instead of 4-20 mA as input, one bit more is used resulting in an improvement in the resolution. In order to convert this input value to a physical one, scaling is necessary. Scaling consists on enlarging or diminishing the value until the desired range.

Firstly, the scaling will be done for the current analog input from the sensor provided by the University. As seen above, max and min values will be 3,277 and 16,384 corresponding to 4 and 20 mA respectively.

$$\text{Max} = 2^{14} = 16{,}384$$

$$16{,}384 \approx 20 \text{ mA}$$

$$3{,}277 \approx 4 \text{ mA}$$

$$819.2 \approx 1 \text{ mA}$$

$$\text{SPAN} = 16 \text{ mA} \approx 13{,}107$$

To get the multiplying factor:

$$\frac{3.2\ m}{13{,}107} = 2.44144350347 \cdot 10^{-4}$$

From the true value which enters the PLC, the minimum value 3,277 is subtracted and the result is multiplied by this factor in order to get the physical value of level.

For example, if 12,000 is the value which enters the PLC:

$$(12{,}000 - 3{,}277) \cdot 2.44144350347 \cdot 10^{-4} \approx 2.13\ m$$

Secondly, the scaling for the voltage input will be done.

Max = 2^{15} = 32,767

32,767 ≈ 10 Vdc

3,277 ≈ 1 Vdc

SPAN ≈ 9 Vdc ≈ 29,490

To get the multiplying factor:

$$\frac{3.2\ m}{29{,}490} = 1.08511359783 \cdot 10^{-4}$$

3.2.2 Ladder logic programming

RSLogix 500 software is a 32-bit Windows ladder logic programming package for the SLC 500 and MicroLogix® processors. RSLogix 500 is compatible with SLC 500 and MicroLogix programs created with any of Rockwell Software's programming packages.

The main screen in RSLogix 500 is:

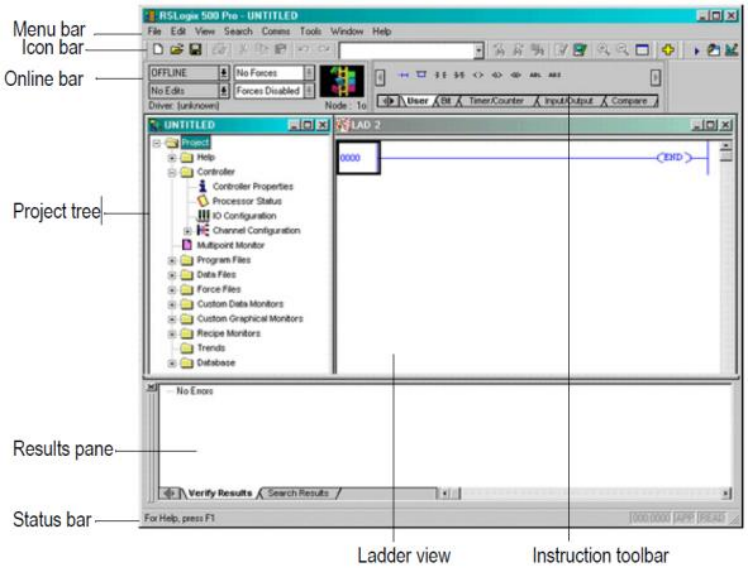


Fig. 3.14 RSLogix 500 main screen [21]

A brief explanation of these bars is found in the RSLogix Getting Results Guide:

- Menu bar - Select functionality from the menus that appear as you click each selection on this bar [21].

- Icon bar - The icon bar contains many functions that you will use repeatedly as you develop and test your logic program. If you want to know what any of the icons represent, RSLogix 500 can tell you. Move your cursor over the icon, and floating ToolTip window appears to tell you what the icon is used for [21].

- Online bar - See at a glance the processor mode and whether you have online edits or forces present. You can also view the communications driver and node number [21].

- Project tree - This view contains all the folders and files contained in your project. You can usually click an icon in this tree and then click the right mouse button for a menu that applies only to the icon selected. For example, if you click the right mouse button on a program file, you see options to rename the program file, open the program file, hide the program file, or reveal properties of the program file [21].

- Status bar - Look here for ongoing status information and prompts as you use the software [21].

- Results pane - Displays the results of a Find All search or a verification procedure. You can hide this pane or place it anywhere on your screen [21].

- Ladder view - This is where you edit your ladder logic. You can view several program files at the same time [21].

- Instruction toolbar - Displays instruction mnemonics in tabbed categories. When you click on a category tab the instruction toolbar just above it changes to show that category of instructions. Click an instruction to insert it in your ladder program [21].

Communications from RSLogix 500 take place through another software package, called RSLinx Classic. To do this, the RSWho function in RSLinx is very useful, the remote device shown must be opened, if everything is OK, the processor should be seen now. If not, there is a communication problem which must be solved before continuing programming.

When a new project is created, the chassis and the processor must be selected, and then the IO configuration, meaning that all the inputs and outputs modules must installed must be declared in the RSLogix. The result is:

- Rack 1: 1746-A10 10 slot rack
- Slot 0: 1747-L532C/D, CPU 5/03 Memory 16K OS302

- Slot 1: 1746-NI4, 4 analog channel input module
- Slot 2: 1746-OB8, 8 digital channel output module, it will not be used in this project, but as it is installed in the rack, it has to be declared.

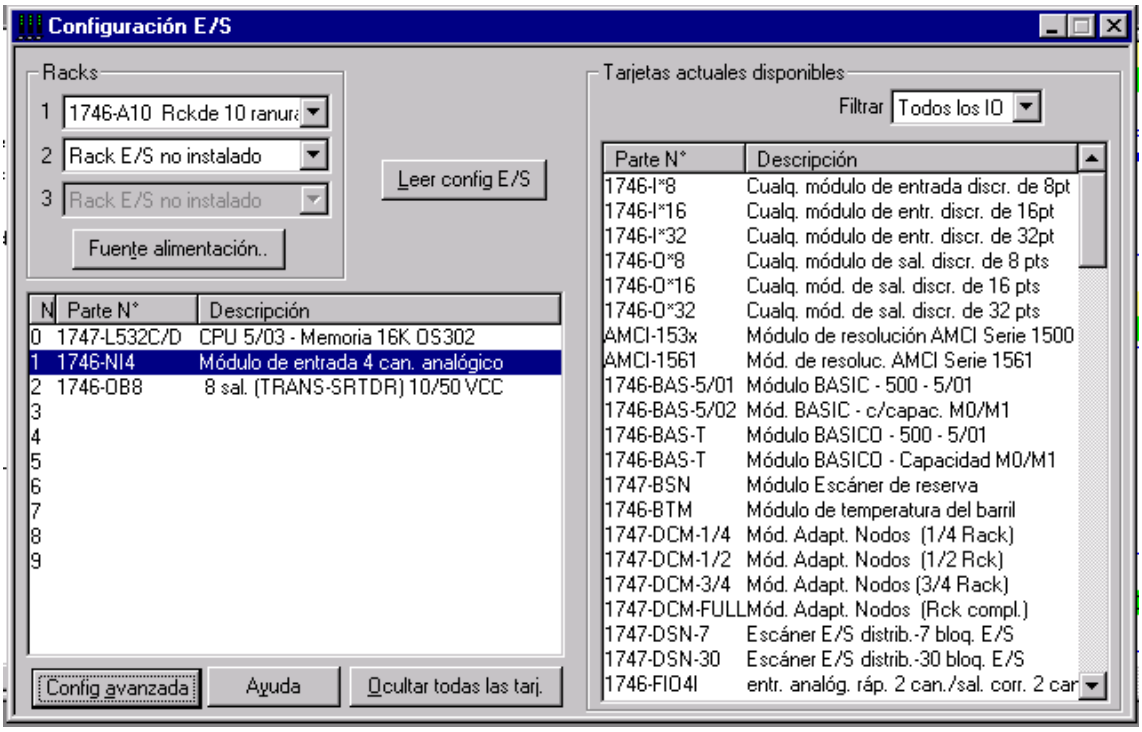

Configuración E/S
Racks
1 1746-A10 Rckde 10 ranur
2 Rack E/S no instalado
3 Rack E/S no instalado
Fuente alimentación..
Leer config E/S
Tarjetas actuales disponibles
Filtrar Todos los IO
Parte N° Descripción
1746-I*8 Cualq. módulo de entrada discr. de 8pt
1746-I*16 Cualq. módulo de entr. discr. de 16pt
1746-I*32 Cualq. módulo de entr. discr. de 32pt
1746-O*8 Cualq. módulo de sal. discr. de 8 pts
1746-O*16 Cualq. mód. de sal. discr. de 16 pts
1746-O*32 Cualq. mód. de sal. discr. de 32 pts
AMCI-153x Módulo de resolución AMCI Serie 1500
AMCI-1561 Mód. de resoluc. AMCI Serie 1561
1746-BAS-5/01 Módulo BASIC - 500 - 5/01
1746-BAS-5/02 Mód. BASIC - c/capac. M0/M1
1746-BAS-T Módulo BASICO - 500 - 5/01
1746-BAS-T Módulo BASICO - Capacidad M0/M1
1747-BSN Módulo Escáner de reserva
1746-BTM Módulo de temperatura del barril
1747-DCM-1/4 Mód. Adapt. Nodos (1/4 Rack)
1747-DCM-1/2 Mód. Adapt. Nodos (1/2 Rck)
1747-DCM-3/4 Mód. Adapt. Nodos (3/4 Rack)
1747-DCM-FULL Mód. Adapt. Nodos (Rck compl.)
1747-DSN-7 Escáner E/S distrib.-7 bloq. E/S
1747-DSN-30 Escáner E/S distrib.-30 bloq. E/S
1746-FIO4I entr. analóg. ráp. 2 can./sal. corr. 2 car
N Parte N° Descripción
0 1747-L532C/D CPU 5/03 - Memoria 16K OS302
1 1746-NI4 Módulo de entrada 4 can. analógico
2 1746-OB8 8 sal. (TRANS-SRTDR) 10/50 VCC
3
4
5
6
7
8
9
Config avanzada
Ayuda
Ocultar todas las tarj.

Fig. 3.15 I/O Configuration

In order to enter the logic program, the instruction toolbar must be used. Initially, the program file will only have the end rung, so a new rung must be added using the icon from the user toolbar.

In this project, two programs files have been programmed. One program per each sensor, so firstly the program for the current output sensor will be shown. In this first case, the SCP (Scaling with Parameters) function has been used.

In this function the input memory direction, with its maximum and minimum, the scaled maximum and the scaled minimum must be declared, as well as the output memory direction.

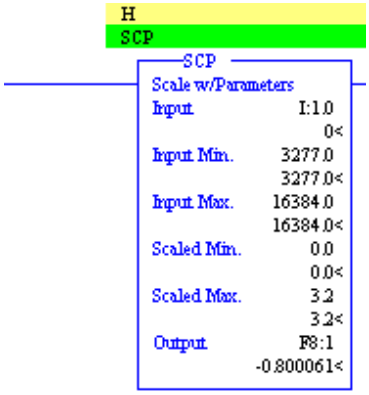
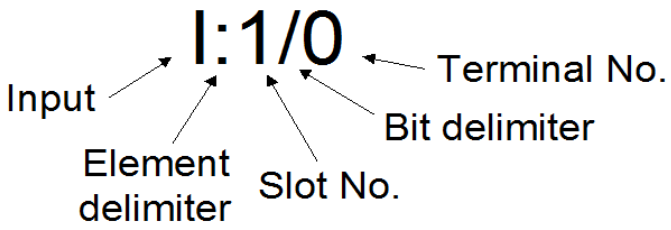


Fig. 3.16 SCP function

In the print screen above, it is possible how addressing to the memory directions is done:

- I:1.0, SOURCE, which indicates that the file type is an input, from the first slot, and the terminal number is 0.
- F8:1, H (height), which indicates that the file type is a float number, the file number is the eight, and the bit number is 1. So, in that direction the height will be directly calculated.

Below, it is possible to see exact explanation of the addressing format:



In this function the input memory direction, with its maximum and minimum, the scaled maximum and the scaled minimum must be declared, as well as the output memory direction.

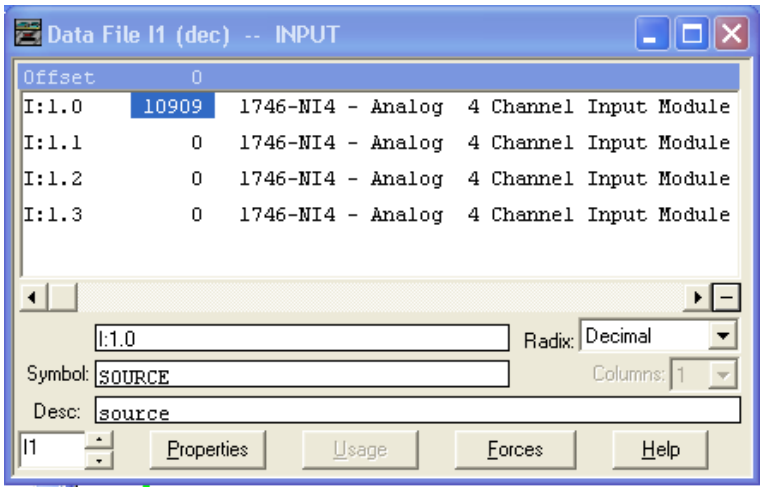


Fig. 3.17 Input data file window

Once the height is known, and considering that the desired data are height, pressure and volume, it is pretty easy to calculate the rest of magnitudes in different new rungs.

As stated before in this project, $P=\rho \cdot g \cdot h$, and there are two ways of calculating that, the first one would be using the multiplying function from the math toolbar, but as it is

only useful to multiply A·B, that procedure has been dismissed. The other way of calculating pressure is by using the compute (CPT) function.

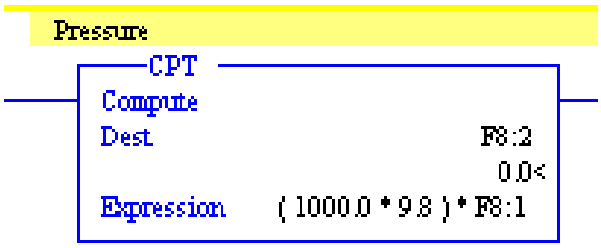


Fig. 3.18 Pressure CPT function

Since it is known that the liquid which is going to be measured is water, and that the measurement is going to take place in the earth's surface, density and gravity can be taken as parameters equal to 1000 kg/m^3 and 9.8 m/s^2 respectively. Therefore, the function is written directly, these two parameters times the height gives the pressure, which is allocated in F8:2.

- F8:2, PRESSURE, which indicates that the file type is a float number, the file number is the eight, and the bit number is 2. So, in that direction the pressure will be stored in Pascals, which is the SI unit.

After that, in a new rung, the final magnitude which is volume will be computed. The procedure is the same, using the next formula:

$$V = \pi \cdot r^2 \cdot h \qquad Equation\ 3.5$$

Now, the known parameters are pi, which equals 3.14159, and the radius of the water pipe, which is 3 inches, approximately 7.5 cm. It has to be noticed that in order to make the equation have the right result, everything must be in SI units, so although pi is an adimensional number, the radius must be written in metres, resulting in r = 0.075m. Therefore, the compute function in the ladder would look like this:

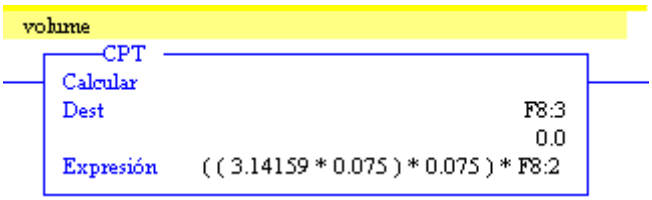


Fig. 3.19 Volume CPT function

- F8:3, VOLUME, which indicates that the file type is a float number, the file number is the eight, and the bit number is 3. So, in that direction the volume will be stored in cubic metres (m^3), which is the SI unit.

Fig. 3.20 End rung

Finally, each program has to finish with an end rung like the one above. So, the full program with comments on the function on each rung would look like this:

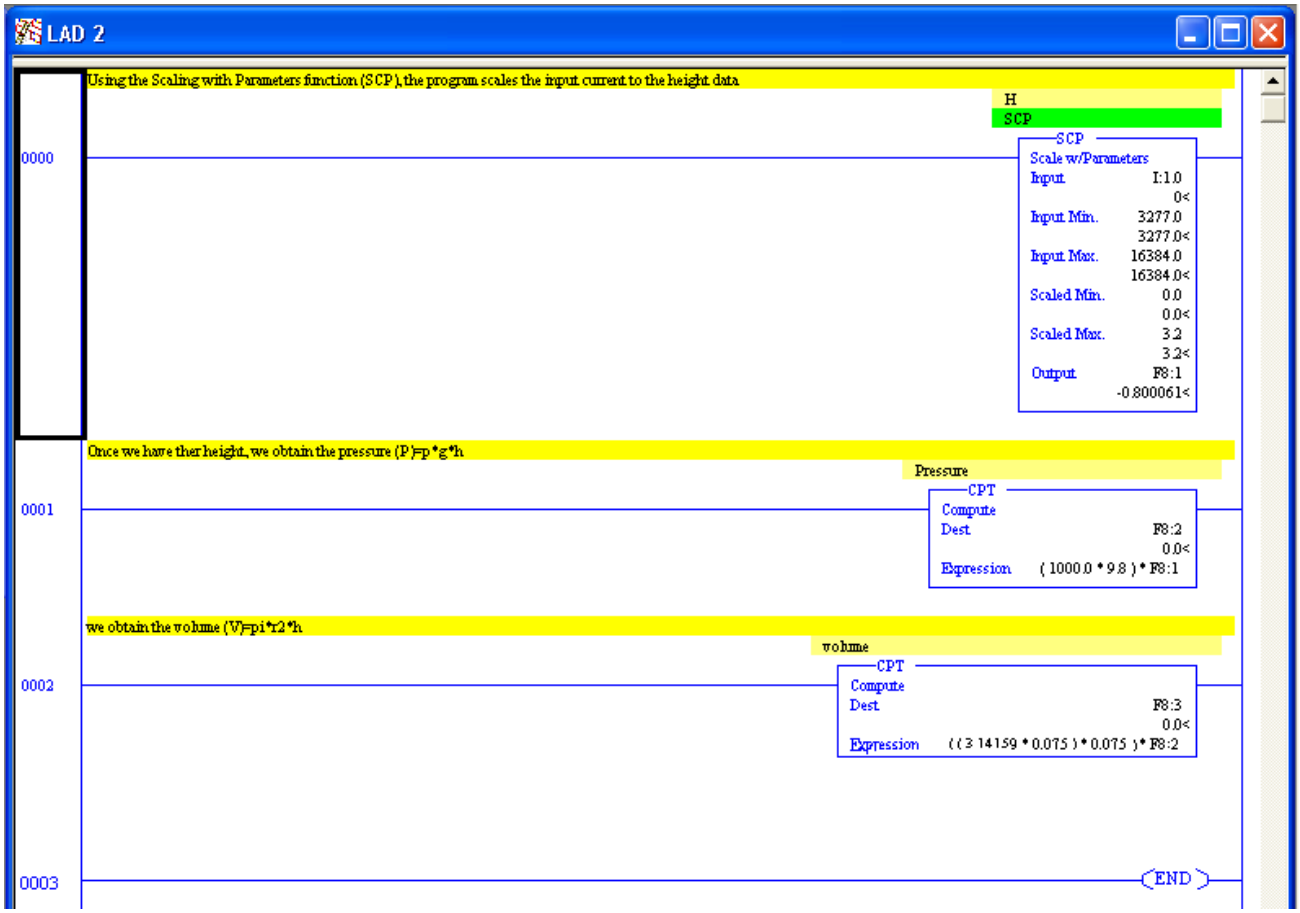


Fig. 3.21 Full program for the current output sensor

Summarising in a list the memory directions used for this program:

- I:1.0, SOURCE, input ranging 3277 to 16384.
- F8:1, H (height), in metres (m)
- F8:2, PRESSURE in Pascals (Pa)
- F8:3, VOLUME, in cubic metres (m^3)

Next step is to make a similar ladder program for the voltage output sensor which has been developed in this project. In this case, the scaling has been done step by step instead of using a function which automatically performs it.

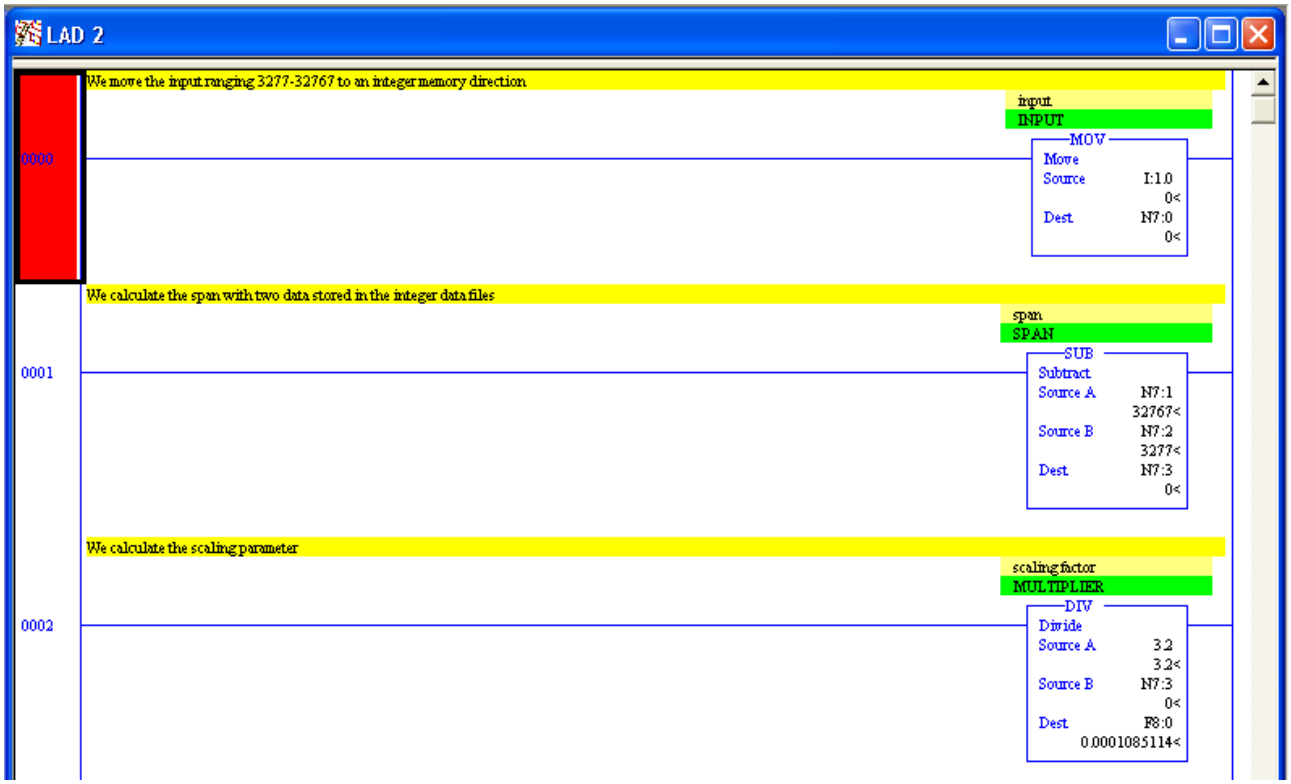


Fig. 3.22 Ladder scaling step by step

In the first rung, 0000, the input from the sensor ranging 3277 to 32767 is moved from the I:1.0, the source, to an integer memory direction N7:0.

- N7:0, INPUT, which indicates that the file type is an integer number, the file number is the seven, and the bit number is 0. So, in that direction the input ranging 3277 to 32767 will be stored.

In the second rung, 0001, the SPAN is calculated with the subtract function from the math toolbar, this function operates A-B. In this case, A is the integer stored in N7:1 and B is the integer stored in N7:2. The result of this operation is saved in N7:3.

- N7:1, MAX, which indicates that the file type is an integer number, the file number is the seven, and the bit number is 1. So, in that direction the maximum input possible, 32767 is saved.

- N7:2, MIN, which indicates that the file type is an integer number, the file number is the seven, and the bit number is 2. So, in that direction the minimum input possible, 3277 is saved.

- N7:3, SPAN, which indicates that the file type is an integer number, the file number is the seven, and the bit number is 3. So, in that direction the input span, which is 29490, is stored.

Finally, in the third rung, 0002, the scaling factor which will multiply every input is calculated. This factor is obtained dividing the 3.2 m of height which has the water pipe between the span stored in N7:3. This is computed with the divide function from the math toolbar, and the result is stored in F8:0.

- F8:0, MULTIPLIER, which indicates that the file type is a float number, the file number is the eight, and the bit number is 0. So, in that direction the scaling factor is stored.

The rest of the program is pretty similar to the one for the current sensor. It is studied below:

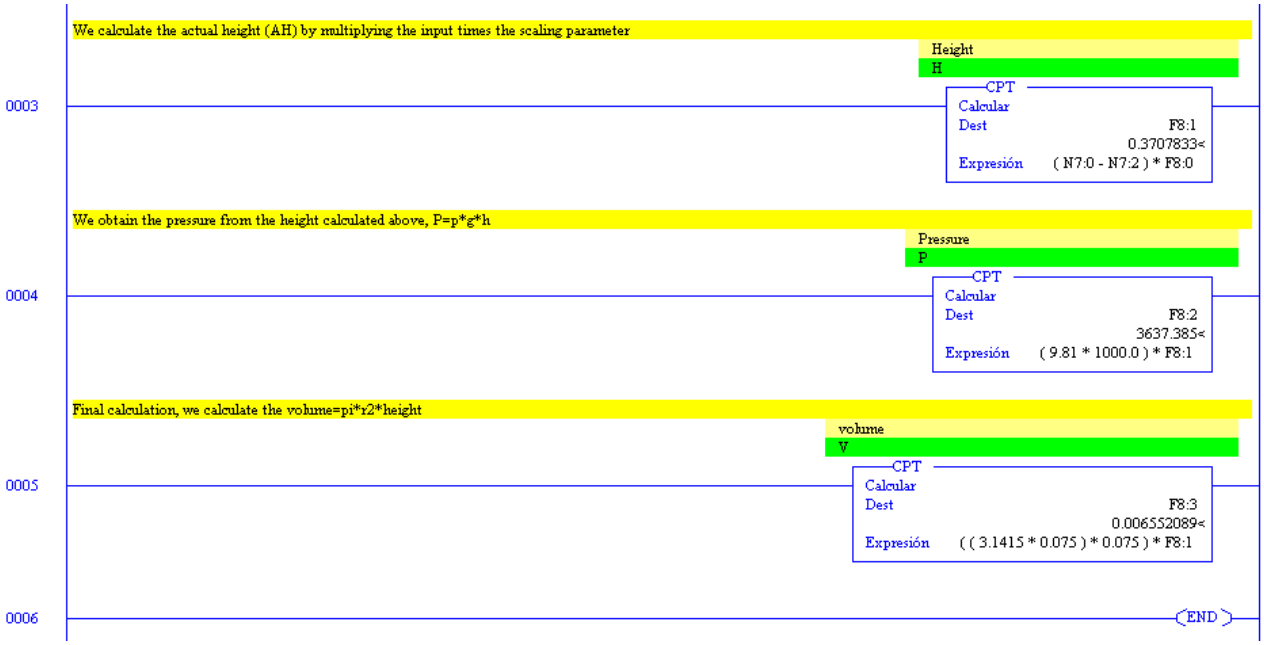


Fig. 3.23 Ladder program for the voltage sensor

Firstly, in rung 0003 the compute function is used again to calculate the height, this calculation is made by subtracting the minimum value to the input true value which enters the PLC, and then by multiplying the result times the scaling factor. The result of this computation is the height which is stored in F8:1 like in the current ladder program.

Next, the procedures in rungs 0004 and 0005 are the same that the ones for the current sensor ladder program, so the memory directions used in this more complex program are going to be listed now.

- I:1.0, MY_INPUT, input ranging 3277 to 16384.
- N7:0, INPUT, input ranging 3277 to 16384 stored in an integer file.
- N7:1, MAX, maximum value that the input can achieve, 32767.
- N7:2, MIN, minimum value that the input can achieve, 3277.
- N7:1, SPAN, the difference between the maximum and minimum possible inputs.
- F8:0, MULTIPLIER, scaling factor.
- F8:1, H (height), in metres (m)
- F8:2, P (pressure) in Pascals (Pa)
- F8:3, V (volume), in cubic metres (m^3)

3.3 Human Machine Interface (HMI)

RSView32™ is a Windows®-based software program for creating and running data acquisition, monitoring, and control applications.

Designed for use in Microsoft® Windows Server 2003, Windows XP and Windows 2000 environments, RSView32 contains the tools you need for creating all aspects of a human-machine interface, including real-time animated graphic displays, trends, and alarm summaries. RSView32 integrates easily with Rockwell Software, Microsoft, and other third-party products to maximize the power of ActiveX®, VBA, OLE, ODBC and OPC® technologies [22].

There are two packages:

- RSView32 Works contains both development and runtime software. Use this software to develop and run RSView32 applications.
- RSView32 Runtime contains only runtime software. Use this software to run applications developed in RSView32 Works.

3.3.1 Control Philosophy

Depending upon the application and the requirements of the control specification, there are different techniques that can be applied. This would greatly depend upon where the 'control' of the system lies and what is required from the SCADA system. The different methods of control are [23]:

- Full SCADA Control. This method entails the control being passed over to the PC and the SCADA software running. All of the logic and sequential control (normally done by a PLC programme) is processed by SCADA. Inputs to the system may be 'real' plant devices which are simply passed through a PLC (acting like an expensive data bridge) onto the PC where the SCADA programme reads the inputs. Similarly 'real' plant output devices may be driven via a PLC but controlled by the SCADA programme. Thus the PLC does not have any 'decision' making within this type of control Philosophy. Besides utilising 'real' I/O, mimicked I/O can be created using graphics within the SCADA programme.

- Full PLC Control. The PLC will have full control of the plant actions and the PLC programme will determine the plant operation. The SCADA programme will simply be used as a data collection point and display information for the user/operator. However the user/operator cannot control the plant from the PC/SCADA, neither can data nor parameters be changed within the PLC programme.

- Shared Control. This is a mixture of the two above methods, and is the most common way to utilise SCADA.

In this project, no control is done and only monitoring is made due to the kind of pump installed, which cannot be automatized.

3.3.2 Starting a project

To start a New project, some parameters must be set up using the file tree.

Firstly, the cannel configuration must be selected. Next, if RSLinx is running, configured and online with the PLC in use, the node configuration should be as easy as selecting the appropriate PLC. This will read the node address of the PLC and check the first stage of the SCADA communications, a failure here would indicate a fault with the set up.

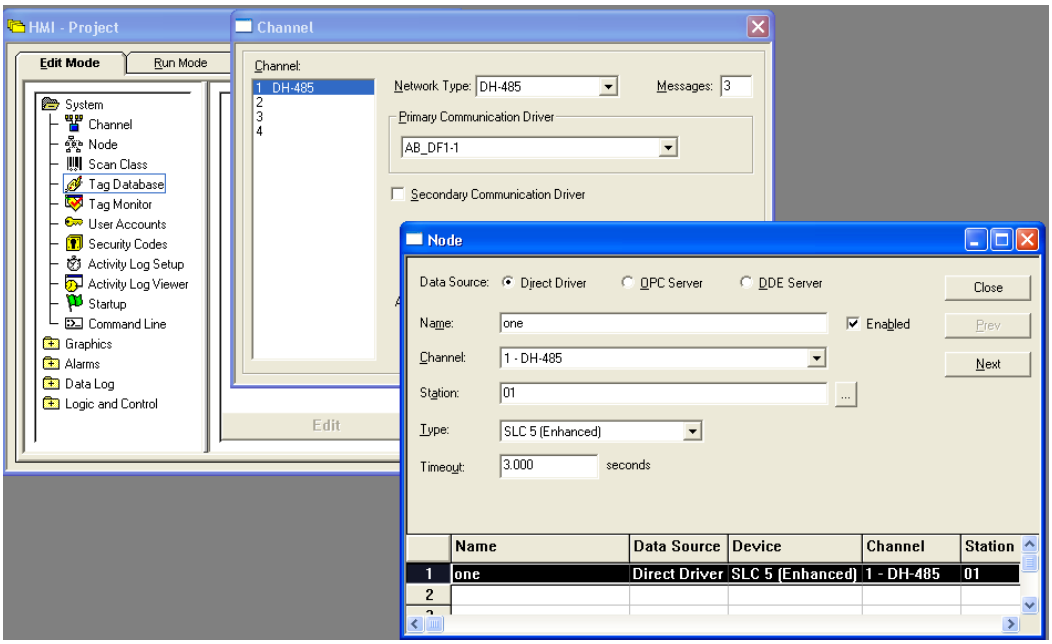


Fig. 3.24 RSView32 file tree, channel and node configuration windows

From the file tree select scan class, the setting within this screen will determine the sample rate for given classes. It should be noted that if there are many devices within a system and they are all on a fast scan class, then there is a high possibility the system will 'clog up' – too much data to be collected within too short a period. Therefore consideration should be given as to which devices really need a fast scan and for which devices would a slower scan be acceptable. User inputs, in the form of a mouse click, require a fast scan (so as not to be missed) hence the default setting for class A to a fast setting will be changed, as shown below.

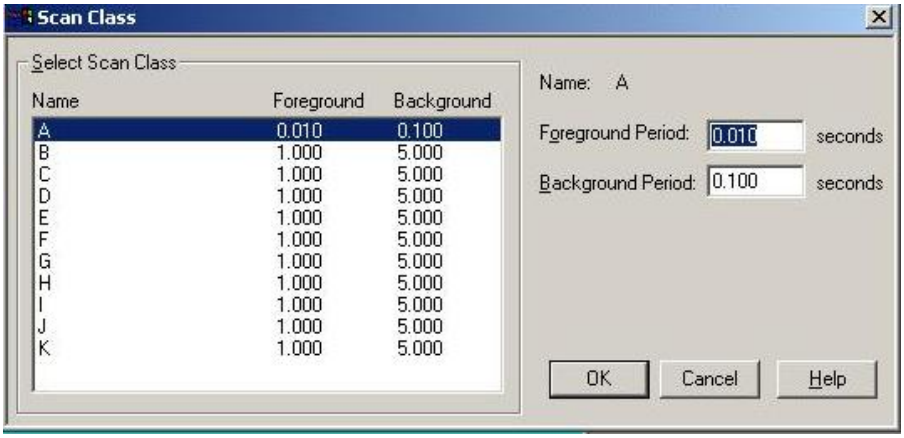


Fig. 3.25 Scan class selection

The remainder of the system set up can be left for now as a basic SCADA program will function with the parameters at default. But in this project also the user accounts option has been configured. Apart from the DEFAULT user, which has all the security

codes allowed, two more user profiles, ADMIN and USER, have been created. ADMIN has the same conditions that the DEFAULT user, and its password is “admin”, this will be required as soon as the project is run. The USER only has access to tags and options labelled with codes A-D.

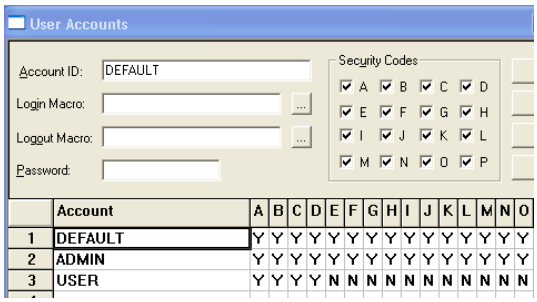

User Accounts
Account ID:
DEFAULT
Login Macro:
Logout Macro:
Password:
Security Codes
A B C D
E F G H
I J K L
M N O P
Account
A B C D E F G H I J K L M N O
1 DEFAULT Y Y Y Y Y Y Y Y Y Y Y Y Y Y Y
2 ADMIN Y Y Y Y Y Y Y Y Y Y Y Y Y Y Y
3 USER Y Y Y Y N N N N N N N N N N N

Fig. 3.26 User accounts configuration

Now, graphic images, which can represent plant devices, can be created using the drawing tools. Clicking on the display folder a new ‘work screen’ will appear, similar to that shown below.

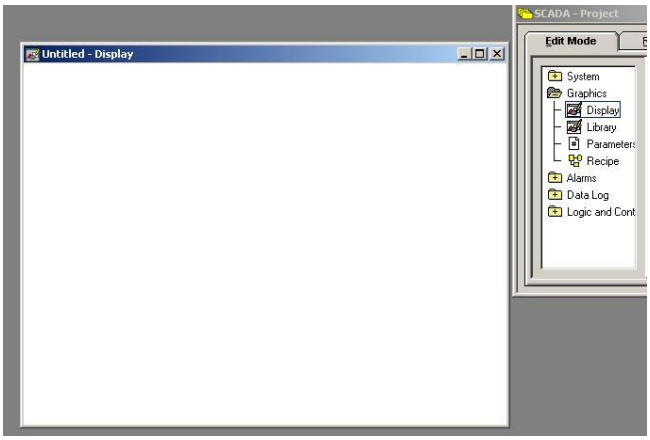


Fig. 3.27 New graphic window

The screen is resized to nearly the maximum, it is useful to leave a small margin to the right of the screen, enabling to see the edge of the file tree, so it can then be quickly brought back to the foreground when required.

Now, the project is ready to start being programmed, graphic images can either be drawn or obtained from the inbuilt libraries. Images can simply represent the appearance of the plant i.e. just a picture that has no other function, or they can represent a plant device that has a control or data acquisition purpose, a programme is built up with a mixture of the two. The control philosophy will determine the way in which the images function [23].

The difference between an image which represent an appearance and the images or text with a function, is that these ones need to be linked to an address, the term used for this is “tag”. This tag may be a real I/O address within a PLC or a memory address within the PC. In the image below different tags can be seen, and the way to configure them in the particular case of this project. The most important thing is to declare the data source, which in this case is the device called “one”, which refers to the PLC, and the address stated in the ladder programming. Apart from that, minimum and maximum values, unit and data type are important for the correct display of the tag.

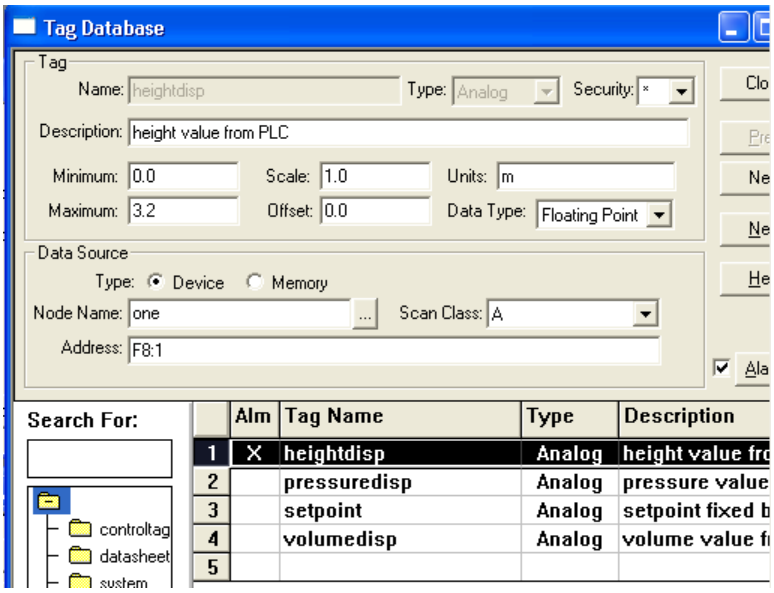


Fig. 3.28 Tag database window

It is possible to see that in this project four tags have been created, they will be further explained later. Another important characteristic which can be declared for each tag are alarms, there are several levels of importance of alarms. In this project, three levels of alarm have been created for the “height tag”.

- Level 1, when the level is below 10 cm, because there is the risk that the application for which the tank is being used runs out of water.
- Level 2, when the level is over 3.10 m, because the limit is 3.20 m and there is a risk of water overflowing the pipe.
- Level 3, the higher level of alarm declared, when the level is over 3.20 m because surely the water is overflowing the pipe.

3.3.3 Graphic windows of the SCADA

In this project seven graphic displays have been designed. They are listed below in the tree file.

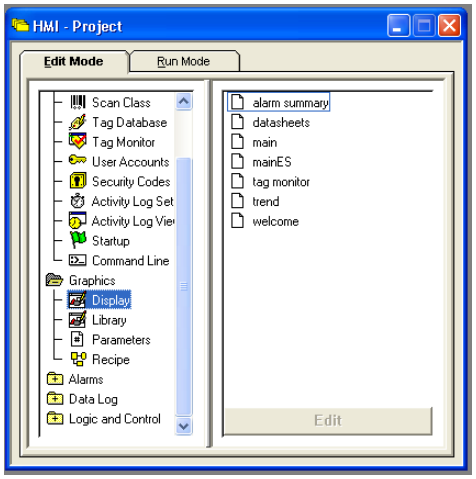


Fig. 3.29 Graphic windows

The initial window is the welcome display, which should allow the user selecting the language between English, Spanish and French. So the flags are the first example of images acting as buttons, in this case they link the user to the main screen.

Fig. 3.30 Welcome window

To configure that, it is necessary to right-click on the image and select animation>touch, there it is possible to touch which action the image will perform when pressed, repeated and released. In this case, the option chosen has been from the navigation group, when pressed, the “main” window will be displayed centered on the screen and the “welcome” window will be closed.

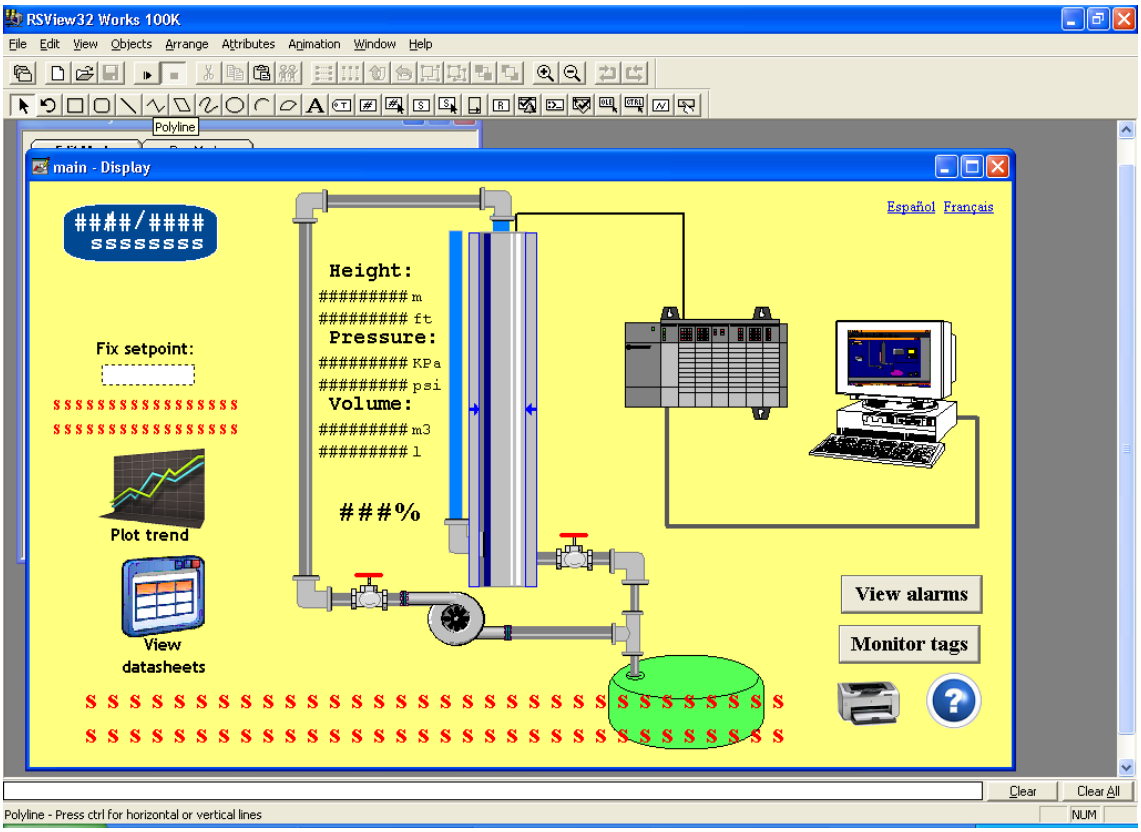


Fig. 3.31 Main window

In the image above, it is possible to see the main windows in the editing mode. This is the most important window, and therefore the most interesting to analyse. Graphically, it tries to represent the environment in the E12 lab, in which there is a big vertical water pipe with a smaller transparent pipe attached to it in order to control the level. This pipe is filled from the top when the pump is connected to the power supply and is emptied the tap in the bottom is opened, the water is both taken from and released to a deposit below the pipe. The other part of the assembly is related to the sensor, which is connected to the input module of the PLC. The final connection is between the PLC and the PC.

Besides, it is possible to see many arrays of “s” and “#” which indicate string and numeric displays. The main displays in this window are the ones in the centre, next to the vertical pipe. There will be displayed the level in metres, for that purpose the tag “heightdisp” has been created. It gets directly the height datum from the PLC memory F8:1. Just below it, another numeric display indicates the height in feet, since it is the imperial unit, very extended in the UK. The same tag “heightdisp” is used for this, and the conversion is made directly in the SCADA, dividing that tag by 0.3048 m, which is the equivalent to 1 ft.

Pressure and volume displays are made in the same way. For pressure the tag “pressuredisp” has been created, but in this case, since it “comes” in Pascals, which is a very little unit, it is displayed multiplied by a 1000 factor making the display unit Kilopascals, which is much more used. For the pounds per square inch (psi), the pressure is obtained in pascals and converted to psi using the equivalence 1psi equals

6,894.757 Pa. In the case of volume, the tag is defined “volumedisp” and it is displayed directly in the first case. But for liquid volumes litres are much more common and volume is also displayed in this unit. To do that, the “volumedisp” is multiplied by a 1000 factor, since there is 1000 l in a cubic metre of water. Finally, another numeric display shows the percentage of filling of the tank.

Apart from that, in order to make the level more visual there are two arrows moving along the grey pipe showing where the level is, this is an automatic option that RSView offers which only needs a tag, in this case the tag used has been obviously “heightdisp”. The other effect is in the transparent pipe next to it, in which the water will also be as high as the level. To make this easier, the grey pipe is 320 pixels high, and the transparent is 290 pixels starting at 30 pixels from the base, trying to copy as much as possible the real pipes in the laboratory. This effect has been made by drawing two rectangles, the white rectangle in the back copies the transparent pipe, and there is an animated blue rectangle in front of it which simulates the water. This blue rectangle has the height animated, with the following code.

```
Heightdisp*100-30
```

Although the code is quite simple, the key to make it work correctly has been to initially give the blue rectangle the maximum height. The reason for this code is that, since the height ranges 0-3.2 and the pipe is 320 height, it needs a 100 multiplying factor. Besides, the transparent pipe starts 30 cm from the base of the grey one, so it is only 290 pixels height and the difference needs to be subtracted.

In order to interact with the SCADA, there are also string and numeric inputs. In this main window there is a numeric input on the left hand side, below the “Fix setpoint” label, actually this tag has been defined “setpoint” and must be a number between 0 and 3.2, so the setpoint will be the level in metres. Once a setpoint is introduced, a message will appear below indicating the operator if he has to fill the pipe, empty it or if the level is in a range of ±10 cm of the fixed one. That message has been programmed with the following function:

```
If  heightdisp < (setpoint-0.1)
Then  "Continue filling the pipe"
Else If  heightdisp > (setpoint+0.1)
Then  "Run the tap until desired level"
else "You have reached the desired level"
```

Another string display is at the bottom of the page. This will only appear showing caution messages when the level is both over 3.10 m and below 10 cm. If not, no message will appear and this lower part of the screen will remain in blank. The code for this message is the following:

```
If heightdisp > 3.1
Then  "CAUTION! The level is over 3.1m and the limit is 3.2m!"
else  If  heightdisp < 0.1
```

Then "CAUTION! The level is below 10cm"
else " "

Next, analysing the rest of the screen buttons and information it is possible to see the last numeric display in this screen is the one in the upper left corner, which shows the time and date. In the upper right corner there are two hyperlinks which display the main window in Spanish and French. On the lower right corner there are two buttons, the first one is for printing the current screen, and the second one makes some help information on what everything on the screen does when the operator clicks on it, and it makes that help messages disappear when he clicks again. The other four buttons: "Plot trend", "View datasheets", "View alarms" and "Monitor tags" will be explained one by one because their function are to display new windows which will be explained next.

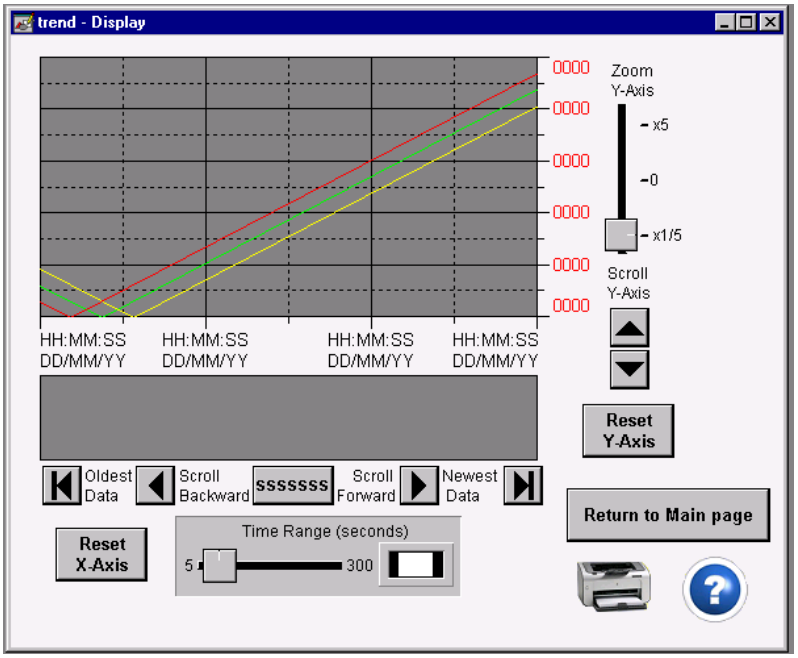


Fig. 3.32 Trend window

In this window, a predefined trend window has been imported from the library, sit i has only been necessary to include the tags to monitor: height, pressure and volume. Buttons allow moving and resizing both magnitude and time axis as well as pausing/resuming the monitoring. The other three buttons apart from the "return to the main page" button have already been explained.

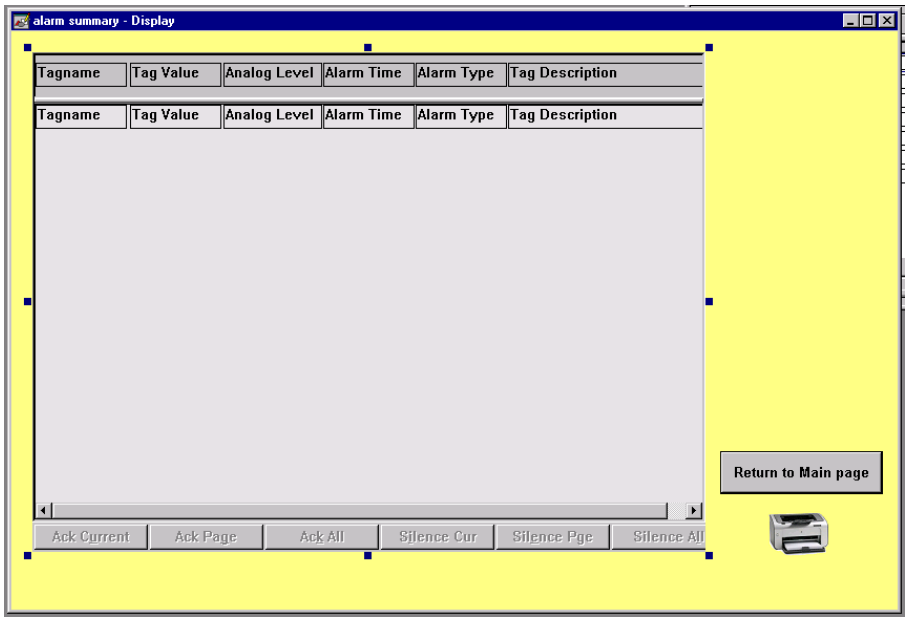


Fig. 3.33 Alarm summary window

In the image above the alarm summary window can be seen. There is a big table which is a predefined function from RSView32, but the information displayed must be selected. In this case that information is:

- Tagname
- Tag value
- Analog Level
- Alarm Time
- Alarm Type
- Tag Description

In the windows below, the tag monitor window is shown in both editing modes. This is also a predefined function, but the tags which are going to be monitored must be written in the first column after double clicking on the table. This table will show the current value, the state, and a description of the tag.

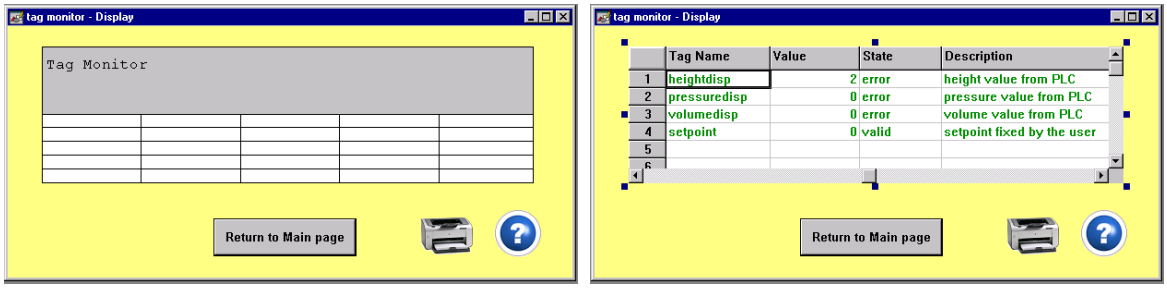

tag monitor - Display
Tag Monitor
Return to Main page
tag monitor - Display
Tag Name
Value
State
Description
1 heightdisp 2 error height value from PLC
2 pressuredisp 0 error pressure value from PLC
3 volumedisp 0 error volume value from PLC
4 setpoint 0 valid setpoint fixed by the user
Return to Main page

Fig. 3.34 Tag monitor window

The last window is “datasheets” and it should allow the visualization of the datasheets from the two sensors, and the installation instructions and user manual of the 1746-NI4, the input module of the PLC.

Fig. 3.35 Datasheets window

The problem with this is that this ActiveX function also requires Visual Basic, and it is not available in the laboratory computer. This also explains the reason why it has not been possible to implement a list box instead of using plain text acting as hyperlinks.

4. Testing & Analysis

Now, the design of the project is finished, so it is the time to develop and test the level sensing system designed. Firstly, the sensor output will be tested. Then, the amplifying circuit will be simulated and implemented. After that, the ladder program will be verified and download to the PLC. Finally, with the aid of the RSLinx for the communications, the SCADA windows will be run.

4.1 Sensor

4.1.1 The transducer

Firstly, once the sensor had been chosen and purchased, the first step was to get its output function. In order to do that, the laboratory environment was tried to be reproduced in a room at home. Below it is possible to see some photos of the assembly.

Fig. 4.1 Water pipe at home

In the image it can be seen the water pipe used to test the sensor, it measures 2.10 metres and similarly to the one in the laboratory, a transparent tube has been attached to control the level. Similarly to the laboratory one, it is filled from the top and at the

bottom, a tap has been installed to empty it. In the image, it is possible to appreciate that the pipe has been marked with the height and the litres, so there were two magnitudes to take as reference.

Furthermore, the transducer input was connected to a small hose with a weight on the tip so it sank to the bottom of the pipe. Apart from that, since the transducer pins are quite easy to bend, it was installed on a breadboard placed on a shelf near to the top of the pipe, so power supply and output wires ran from the top of the pipe until the voltage source and the amplifying circuit. Images below try to show these concepts.

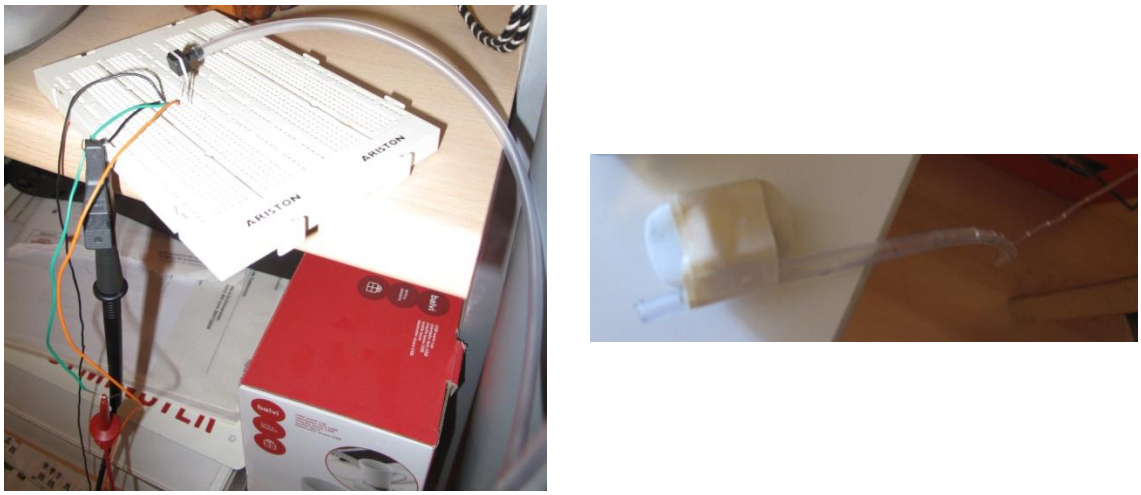


Fig. 4.2 Sensor breadboard assembly

Now, everything was prepared to make some measurements and deduce the output function of the sensor. Just as a reminder, the sensor must be fed with 3.3 Vdc.

Fig. 4.3 Measuring the sensor output

The results are shown in the table below, the voltage values were taken each 10 cm of depth:

Height (m)	Voltage (V)
2,00	1,423
1,90	1,395
1,80	1,330
1,70	1,264
1,60	1,219
1,50	1,151
1,40	1,095
1,30	1,052
1,20	1,000
1,10	0,948
1,00	0,885
0,90	0,845
0,80	0,780
0,70	0,727
0,60	0,675
0,50	0,614
0,40	0,561
0,30	0,502
0	0,334

With this data, the first step was to do a regression analysis, as expected trend is linear, linear regression analysis has been carried out. The method used will be the least squares, consisting on minimizing the sum of the squares of the difference between experimental and theoretical values. The solution will be of the form y=ax+b, in this case y will be the voltage and x will be the height. To get the equation, the following formula must be substituted:

$$y - \bar{y} = \frac{S_{xy}}{{S_x}^2} \cdot (x - \bar{x}) \qquad Equation\ 4.1$$

Where knowing that n=19:

$$\frac{1}{n}\sum_{i=1}^{n} \mathrm{y}_i \qquad Equation\ 4.2$$

$$\bar{\mathrm{y}} = 0.94$$

$$\bar{\mathrm{x}} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{x}_i \qquad Equation\ 4.3$$

$$\bar{x} = 1.09$$

$$s_{xy} = \frac{1}{n}\sum_{i=1}^{n} x_i y_i - \bar{x}\bar{y} \qquad Equation\ 4.4$$

$$s_{xy} = 0.175387812$$

$$s_x{}^2 = \frac{\sum_{i=1}^{n} x_i}{n} - \bar{x}^2 \qquad Equation\ 4.5$$

$$s_x{}^2 = 0.32094183$$

Substituting in equation 4.1 and simplifying:

$$y - 0.94 = \frac{0.175387812}{0.32094183} \cdot (x - 1.09)$$

$$y - 0.94 = 0.54647851x - 0.5956615759$$

$$\boldsymbol{y = 0.54647851x + 0.344338421}$$

Where, y is the voltage in volts (V) and x the height in metres (m).

It is also possible to compute the correlation coefficient (r), which shows the "quality" of the approach. If r is around 1 the approximation will be very good and if the coefficient is near to 0 the deviation will be quite important.

$$r = \frac{s_{xy}}{s_x \cdot s_y} \qquad Equation\ 4.6$$

Being,

$$s_x = 0.56651728$$

$$s_y{}^2 = \frac{\sum_{i=1}^{n} y_i}{n} - y^2 \qquad \text{Equation } 4.5$$

$$s_y{}^2 = 0.09589666$$

$$s_y = 0.30967186$$

Substituting,

$$r = \frac{0.175387812}{0.56651728 \cdot 0.30967186}$$

$$\mathbf{r = 0.999734108}$$

This means that the quality of the approximation is very good.

Next, the data will be plot using MS Excel, which also allows knowing the regression so it is possible to check the hand computed one.

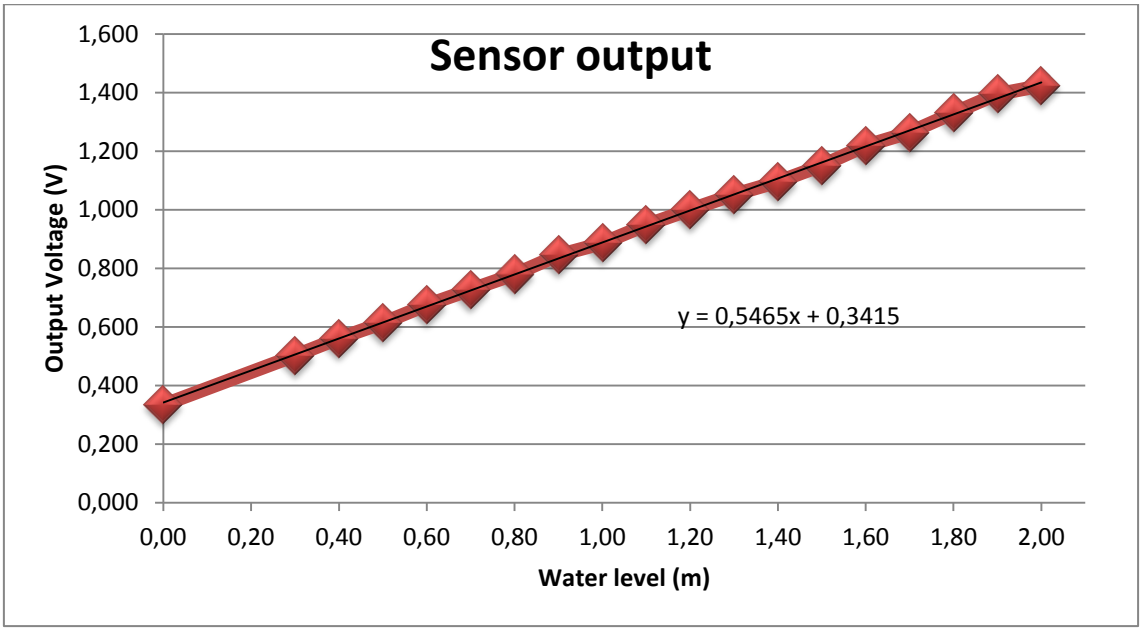


Fig. 4.4 Sensor output function

It is also possible to use excel to obtain other regressions:

- Exponential regression: $y = 0{,}4305 \cdot e^{0{,}6543 \cdot x}$
  This has a correlation coefficient (r) = 0.9772921774
- Polynomical of 2nd order: $y = -0{,}0053x^2 + 0{,}5576x + 0{,}3373$
- Polynomical of 3rd order: $y = 0{,}0119x^3 - 0{,}0414x^2 + 0{,}5867x + 0{,}3325$
- Polynomical of 4th order: $y = -0{,}0007x^4 + 0{,}0145x^3 - 0{,}0447x^2 + 0{,}588x + 0{,}3324$
- Polynomical of 5th order: $y = -0{,}0762x^5 + 0{,}3846x^4 - 0{,}6712x^3 + 0{,}4571x^2 + 0{,}461x + 0{,}3348$
- Polynomical of 6th order: $y = -0{,}1718x^6 + 0{,}9828x^5 - 2{,}0869x^4 + 2{,}0252x^3 - 0{,}896x^2 + 0{,}7069x + 0{,}3337$

It can be seen easily that linear regression is better than exponential, since the graph is much more similar to a straight line than an exponential function. On the other

hand, the higher the polynomial is and the better the approximation will be, but it has been demonstrated that first order polynomial, which is the linear regression, is good enough.

4.1.2 The amplifying circuit

The first test after designing the amplifying circuit was to simulate it on the computer. For that purpose, the PROTEUS software by Labcenter Electronics has been used. Since the sensor was not in the library, a voltage source has been placed doing its function. It is noticeable that a 24 kΩ has been used instead of the 25 kΩ because that is the standardized industrial value.

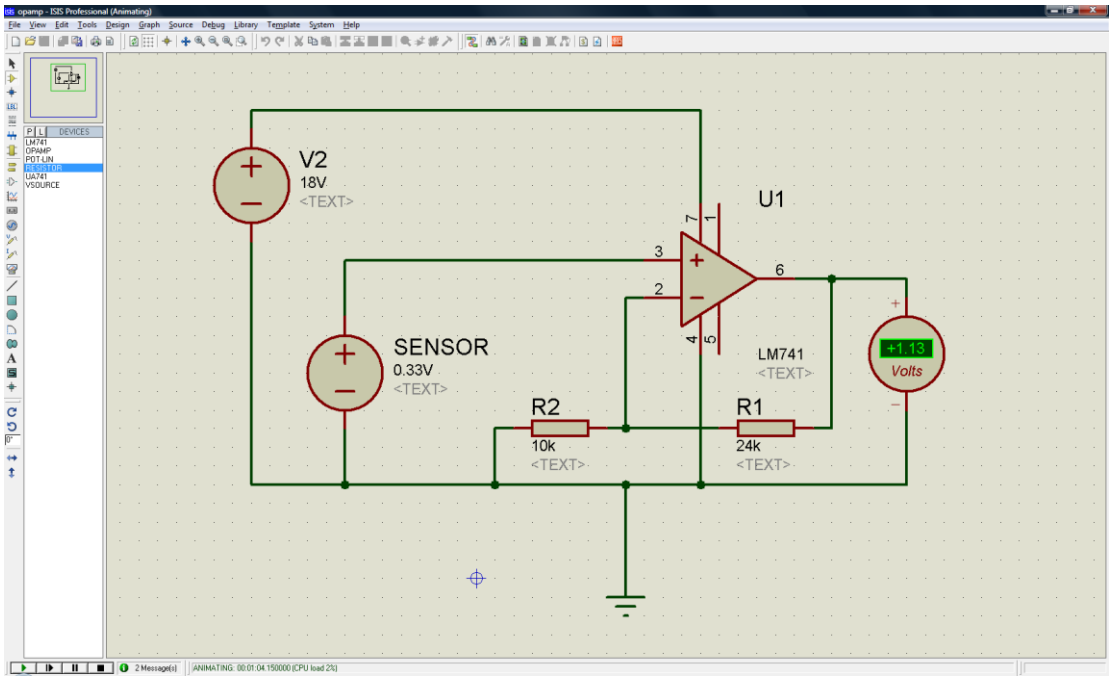


Fig. 4.5 Amplifying circuit running in PROTEUS (I)

$$Av = \frac{1.13\ V}{0.33\ V} = 3.425$$

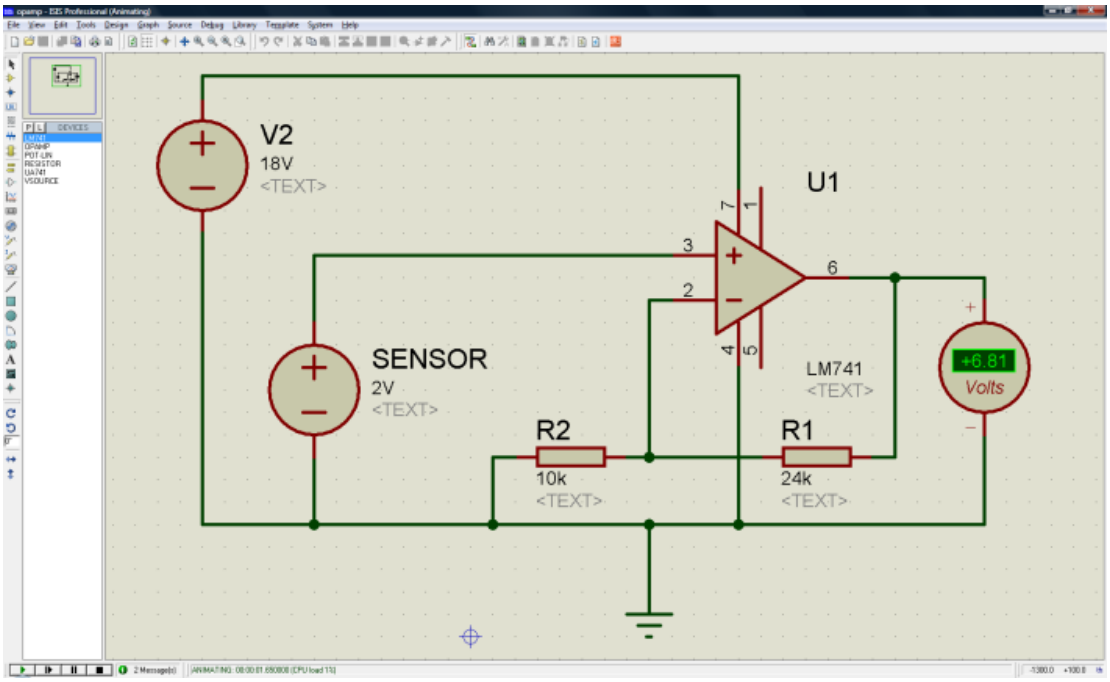


Fig. 4.6 Amplifying circuit in PROTEUS (II)

$$Av = \frac{6.81\ V}{2\ V} = 3.405$$

Once the simulation proved the circuit was correct, it was implemented on a breadboard.

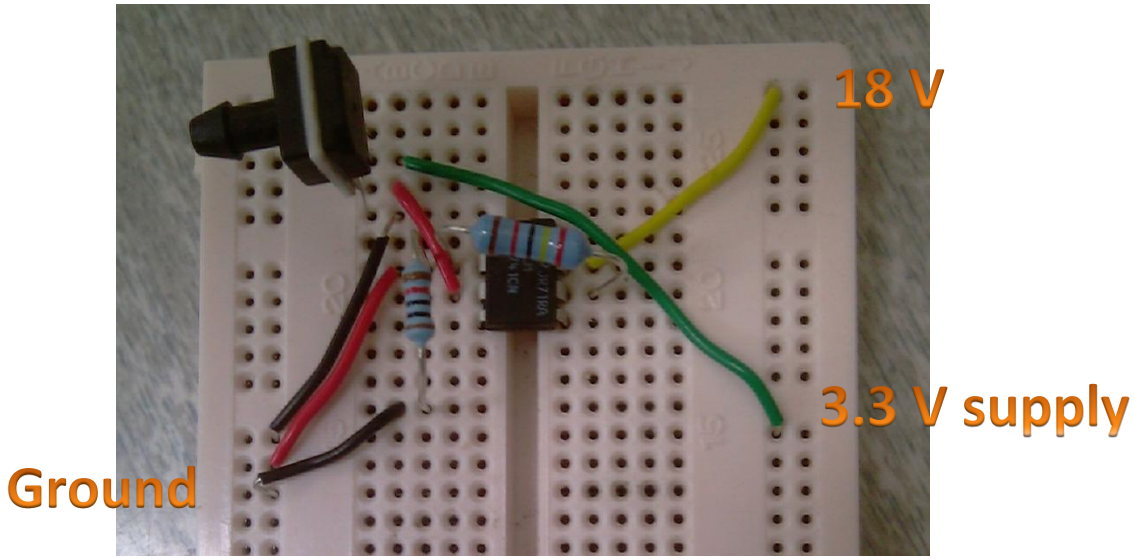


Fig. 4.7 Amplifying circuit on breadboard

This caused a lot of problems, although theoretically it should work. On practice it did not, it worked well with big voltages, but with an input below 2 V approx. it did not

amplify correctly, the output stabilized at 6.7 V approx. The problem was that since it does not require negative voltages, it should work perfectly, but reality shows that in order to amplify correctly low voltages, the negative supply of the amplifier is required or it saturates. Therefore, another source was required, making three voltages sources in total, one of 3.3 V to feed the sensor and the other two of ±18V to feed the amplifier.

So finally, the sensor assembly is:

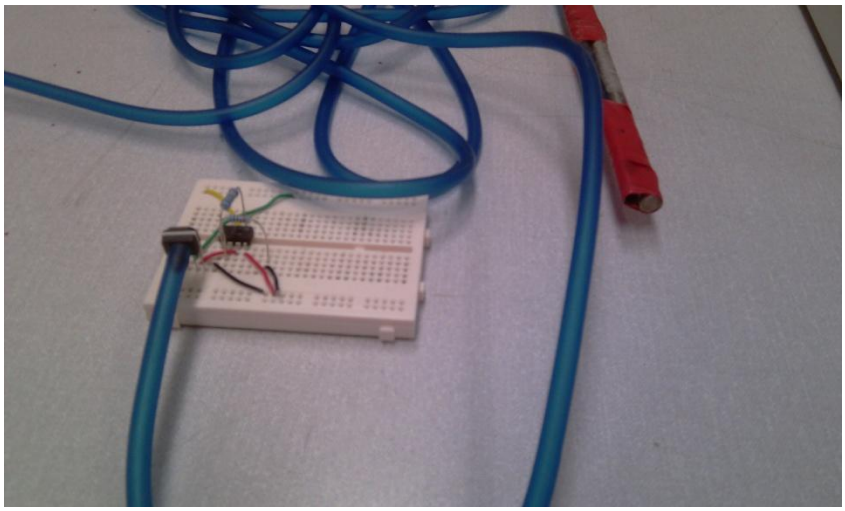


Fig. 4.8 Final sensor assembly

The tip of the hose which is stuck to an iron bar with insulating tape can be seen on the right of the photo. On the image below, it is showed how the hose is fit in the water pipe from the top.

Fig. 4.9 Fitting the sensor hose into the pipe

4.1.3 The current to voltage circuit converter

It has already been mentioned that this part was not implemented in the project. Anyway, it has been simulated with PROTEUS to demonstrate whether it could worked or not, and the results were positive.

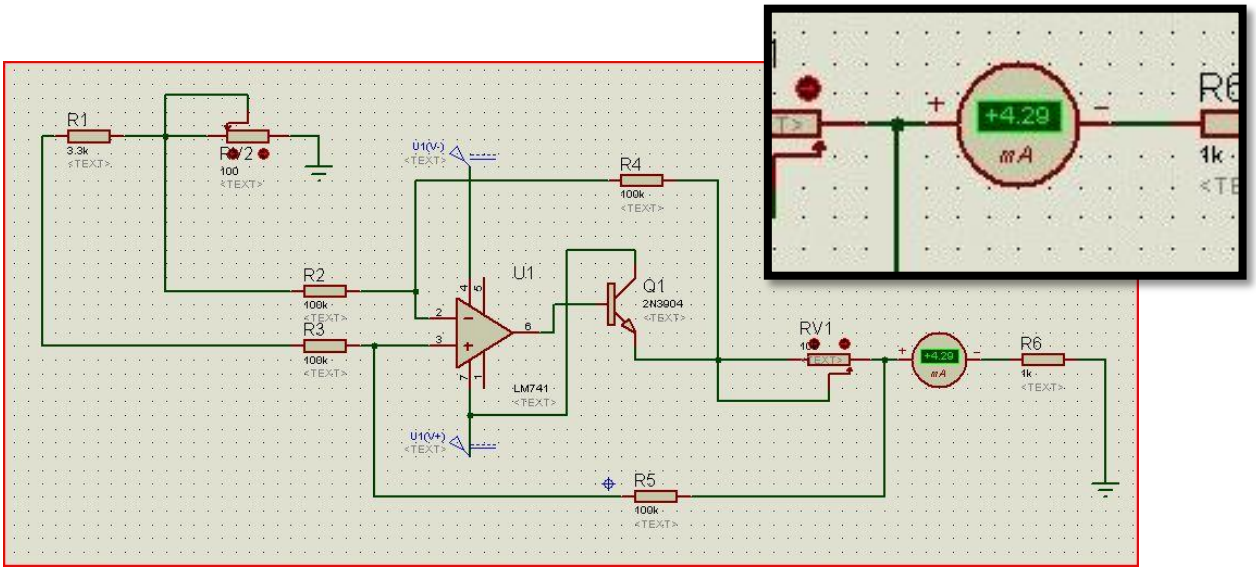


Fig. 4.10 Converting 0V to 4mA

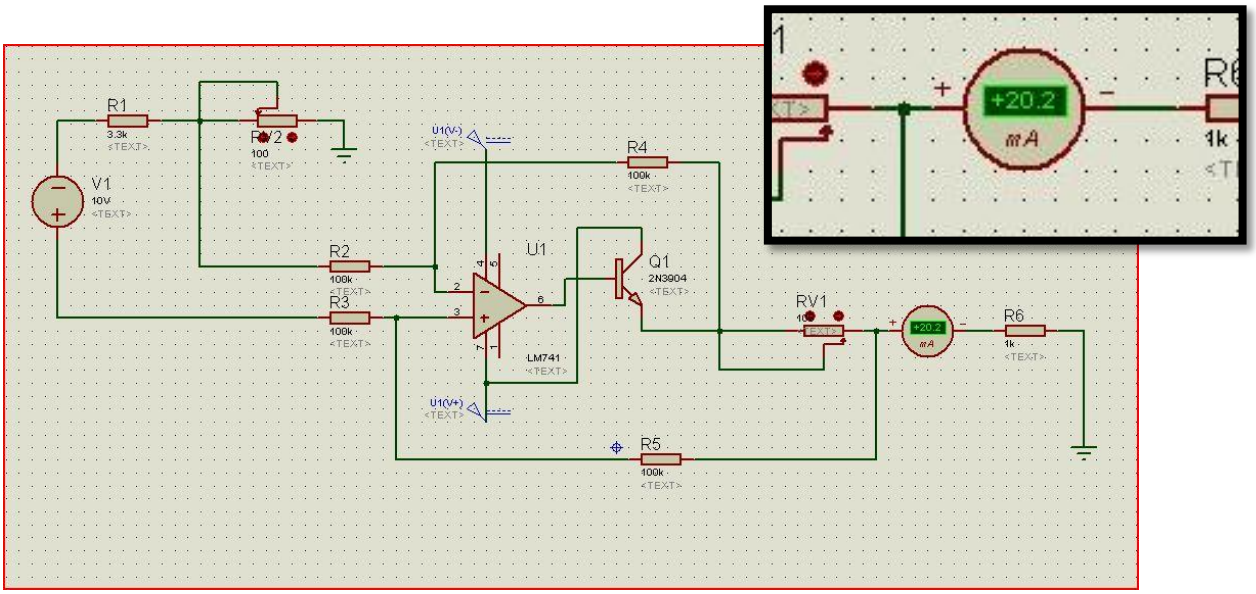


Fig. 4.11 Converting 10V to 20mA

4.2 Testing the ladder logic programming

It has already been showed how to wire the PLC and how to test whether it has communication with the PC by using RSLinx. In order to test the ladder, the first step is to check it using the RSLogix command buttons “Verify file” and “Verify project” which can be seen below:

Fig. 4.12 RSLogix verify buttons

Next, one the problems found have been solved, the online bar status must be changed from “OFFLINE” to “DOWNLOAD”

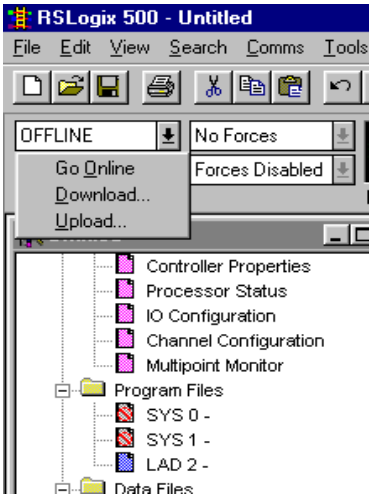


Fig. 4.13 RSLogix online bar

The software will now load the RSLINX driver for downloading and communication to the CPU. The screen will bring up a series of prompts for the operator to acknowledge. Now, the system should be REMOTE RUN, but there is the possibility that it stays in the REMOTE PROGRAM mode, from the same list box the GO ONLINE option must be selected. After that, the PLC must be online, an example of the program running can be seen below.

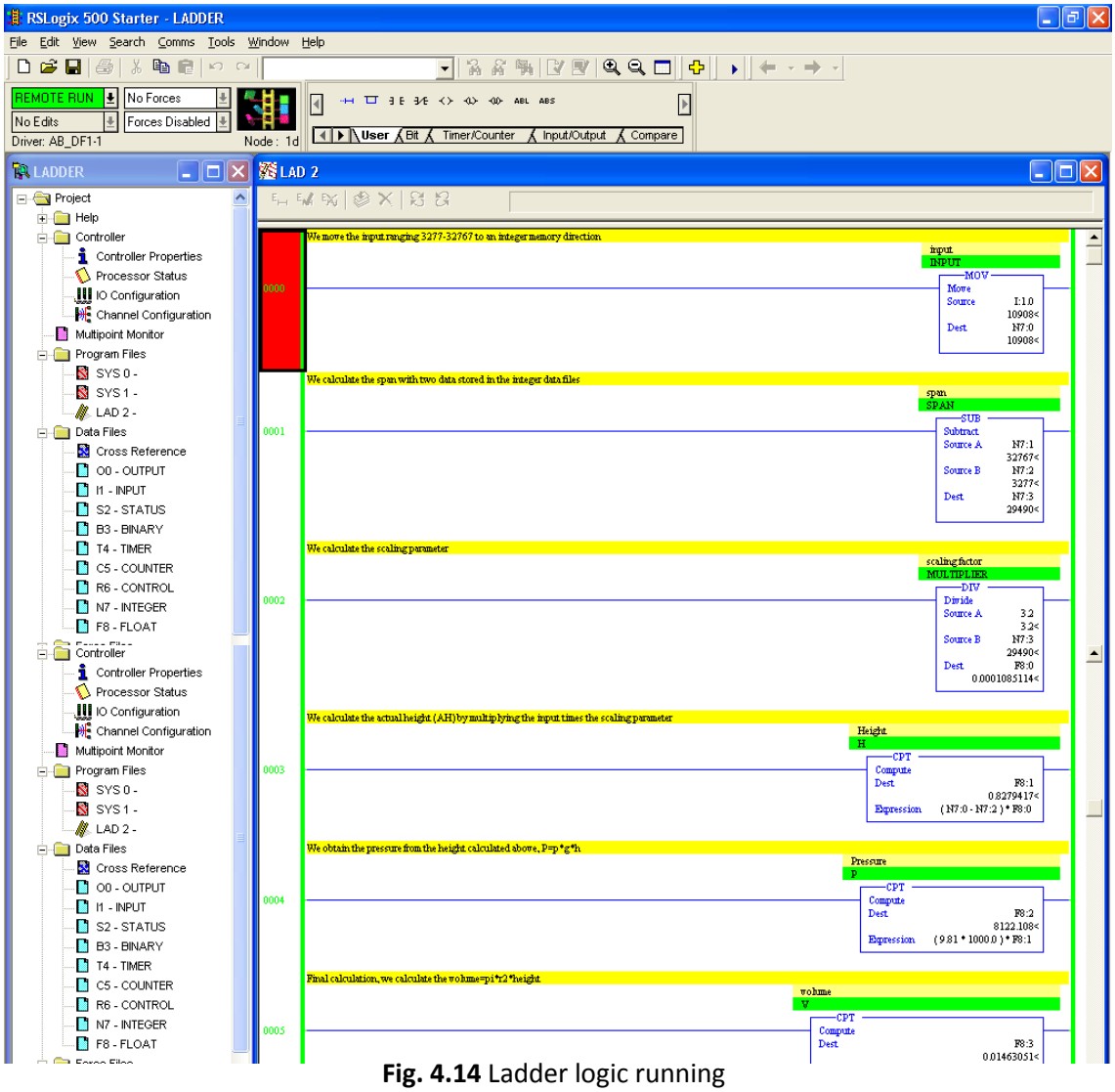


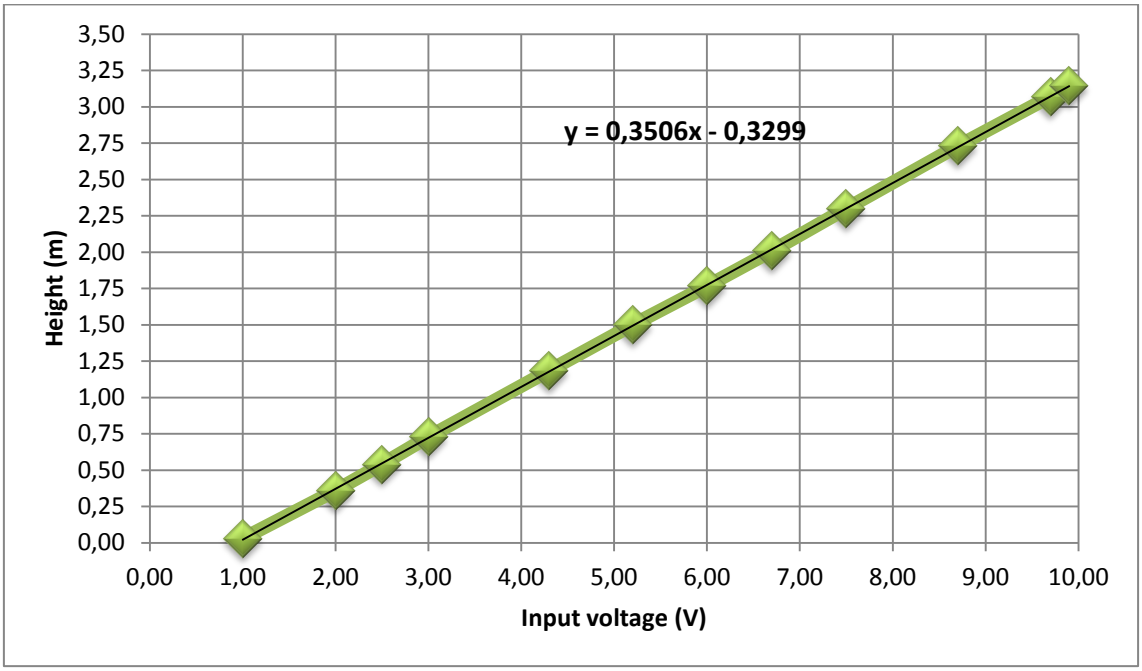
Fig. 4.14 Ladder logic running

A “random” set of samples have been recorded, they have been represented in the following table.

Voltage input (V)	Bit input	Height (m)
1	3550	0.028
2	6602	0.36
2.5	8258	0.54
3	10067	0.73

4.3	14238	1.185
5.2	17136	1.5
6	19548	1.766
6.7	21840	2.01
7.5	24668	2.3
8.7	28523	2.73
9.7	31593	3.07
9.9	32243	3.14

Using Excel to plot the results and get the linear regression:



4.3 Testing the SCADA

Finally, it is the time to test the visual interface, to do that the PLC must be online. Next, from the bar above, the status must be changed from stop to running by clicking on the following button:

Fig. 4.15 SCADA stop-run button

Now, some of the screens will be shown while running:

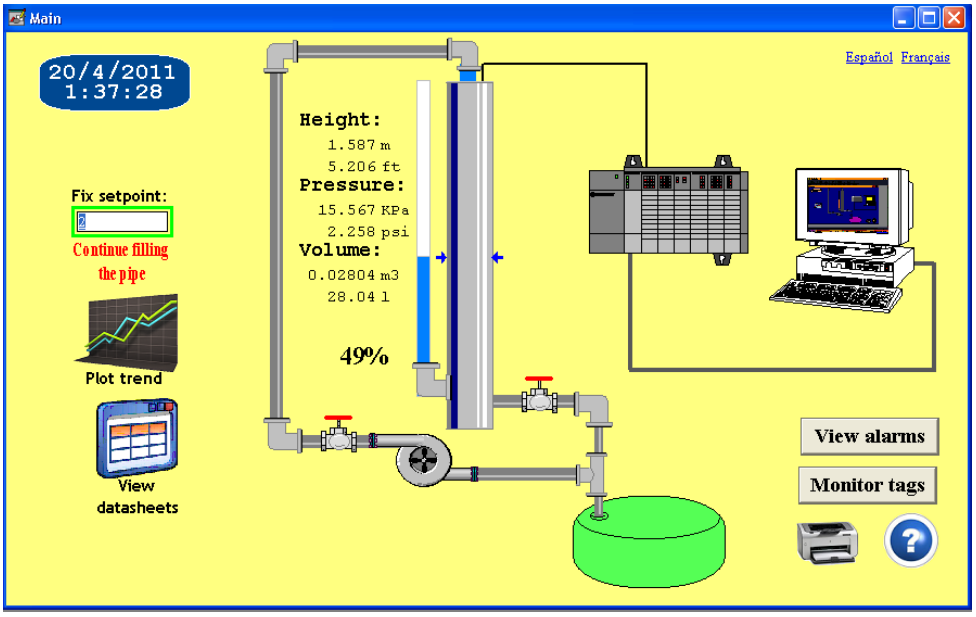


Fig. 4.16 Main window running (1)

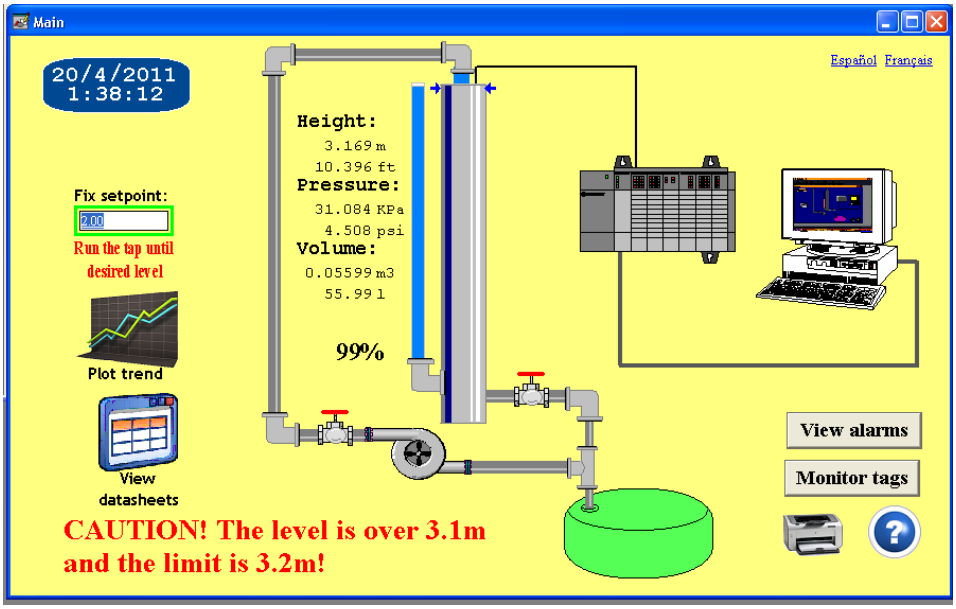


Fig. 4.17 Main window running (2)

It is possible to see that all the main window displays worked well, and the programmed messages too. In the first image since the setpoint is 2 m, and the level is 1.587 m, it encourages the operator to fill the pipe until the desired level. In the second screen, the level is 3.169 m, so an alert message has appeared at the bottom of the screen since the limit is very close. Besides, as the desired level is still 2 m, the recommendation to the operator is to run the tap. Once the main window is opened, tags are started to monitor and their status can be checked with the button on the lower right corner. The window mentioned can be seen below.

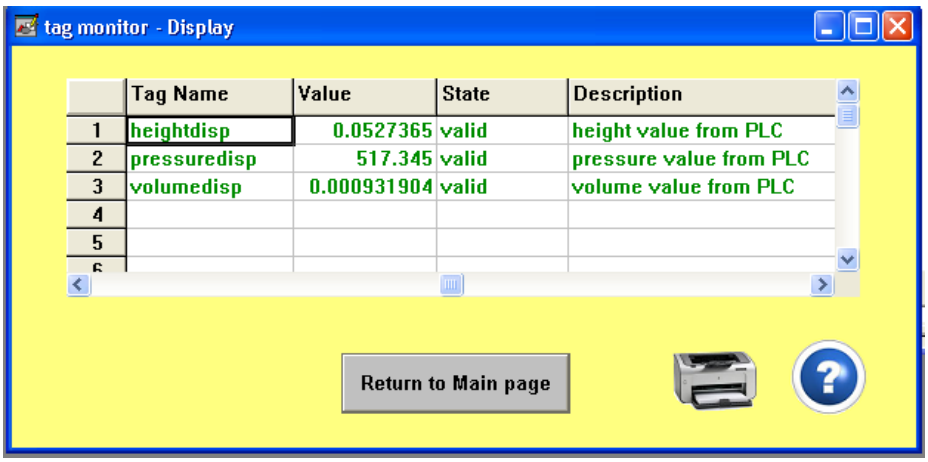


Fig. 4.18 Tag monitor window running

After increasing and decreasing the level very fast, the alarm summary window has the following appearance. Alarms are saved whenever the level is below 10cm, with an alarm level of 1, when the level is over 3.10 m, with an alarm level of 2, and when the level is over 3.20 m, with the highest level of alarm since the water must be falling to the floor. The time when the level comes back to allowed values is also saved.

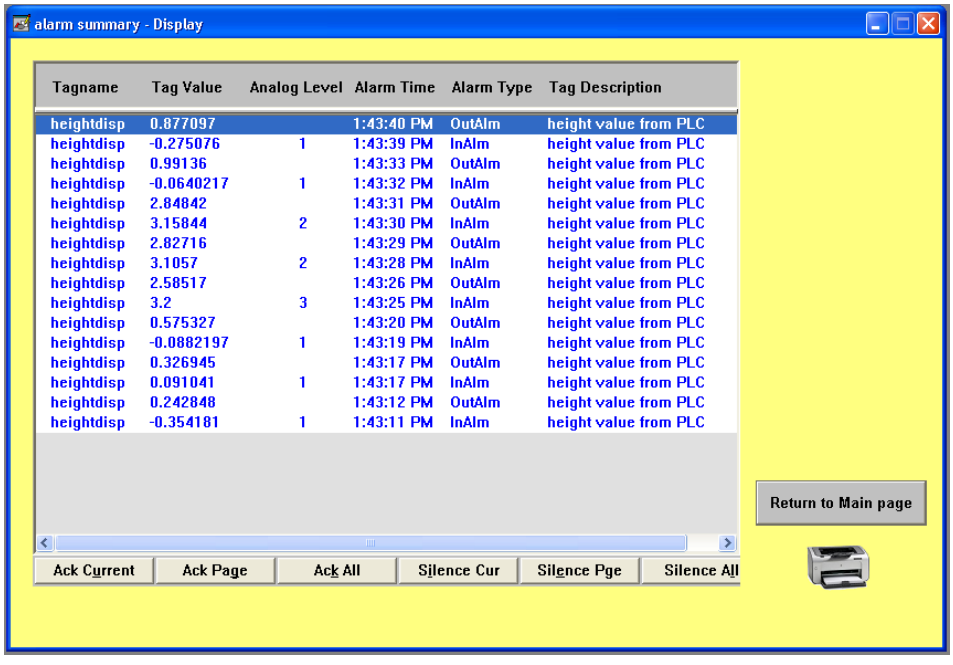

alarm summary - Display
Tagname Tag Value Analog Level Alarm Time Alarm Type Tag Description
heightdisp 0.877097 1:43:40 PM OutAlm height value from PLC
heightdisp -0.275076 1 1:43:39 PM InAlm height value from PLC
heightdisp 0.99136 1:43:33 PM OutAlm height value from PLC
heightdisp -0.0640217 1 1:43:32 PM InAlm height value from PLC
heightdisp 2.84842 1:43:31 PM OutAlm height value from PLC
heightdisp 3.15844 2 1:43:30 PM InAlm height value from PLC
heightdisp 2.82716 1:43:29 PM OutAlm height value from PLC
heightdisp 3.1057 2 1:43:28 PM InAlm height value from PLC
heightdisp 2.58517 1:43:26 PM OutAlm height value from PLC
heightdisp 3.2 3 1:43:25 PM InAlm height value from PLC
heightdisp 0.575327 1:43:20 PM OutAlm height value from PLC
heightdisp -0.0882197 1 1:43:19 PM InAlm height value from PLC
heightdisp 0.326945 1:43:17 PM OutAlm height value from PLC
heightdisp 0.091041 1 1:43:17 PM InAlm height value from PLC
heightdisp 0.242848 1:43:12 PM OutAlm height value from PLC
heightdisp -0.354181 1 1:43:11 PM InAlm height value from PLC
Return to Main page
Ack Current
Ack Page
Ack All
Silence Cur
Silence Pge
Silence All

Fig. 4.19 Alarm summary window running

The last important window is the trend, which can be seen below. It plots the evolution of the selected tags. The y axis shows the magnitude of the current selection, which can be changed by clicking on the tags below the graph, it can also be zoomed and scrolled using the buttons on the right. The x axis shows the time, which can be "moved" using the buttons at the bottom of the screen.

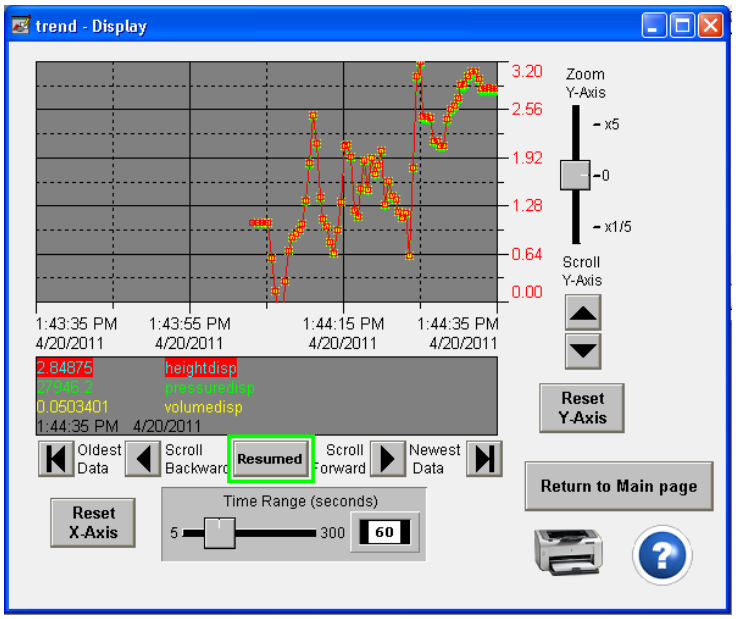


Fig. 4.20 Trend window running

5. Conclusions

The aim of this project was designing and developing a level sensing system. The hardware consisted on a pressure sensor measuring from a vertical water pipe and connected to a PLC which converted the input in height, pressure and volume and sent it to a PC. The conclusions obtained for this project are:

- For this project, the choice was to use the simplest principle to measure level, so a pressure transducer was used.

- Using pressure to measure the level is advisable regardless the dimensions and shape of the tank.

- One of the obtained conclusions with the implementation of this level sensing system is the acquisition of that reading safely and with a greater reliability than the one obtained by an operator.

- An operator would give a subjective reading since in order to read the level correctly it is necessary to be at the same height of the level. So, it would be necessary a ladder or a mechanism to observe the tank level accurately enough when reading above 2 metres height. Besides, this implies a risk for the operator which is completely solved with this application.

- Another factor which can affect to a false reading is the mental fatigue of an operator when doing a repetitive task like reading tank levels, especially in those cases when the number of tanks is very high.

- Another conclusion of this project is the flexibility to increase the number of tanks allowing this application to be used in several industries, simply connecting more sensors to the PLC inputs and adding objects in the SCADA to monitor the level, this allows an operator to supervise with no risk a great number of tanks.

- SCADAs are very powerful tools for real time monitoring and control of an industrial plant. But, the final operator must always be taken into account when designing it since the easiest to use it is, the least errors there will be.

- The alarm configuration allows being proactive with possible risks of both very full or too empty tanks in real time and take actions to correct the incidence avoiding undesirable consequences like non-programmed stops.

- From an economic point of view, this application allows supervision from a control room of as many levels as desired. This is an important advantage if the levels to monitor are in an industry big enough to employ more than one operator to supervise everything. With this application, human resources could be sent to other tasks which improve quality for both the professional task of the operator and the company.

- From a safety point of view, this application allows supervision of the level regardless it is inflammable, corrosive, etc. from a distance safe enough for the operator.

- As a remarkable experience in the development of this application, it is noticeable the behaviour between both theoretical and practical work. Firstly, according to the datasheet of the sensor, it should give a voltage as a function of measured pressure which, after the development of the sensor and the data acquisition has been proved experimentally how the change in the behaviour is almost 50% less with respect to the expected values in the sensor datasheet.

- Another remarkable experience in this topic is related to the problem with the negative supply of the Opamp, although theoretically it is not necessary if the output does not require negative voltages, in practice the opamp saturates when trying to amplify very low voltages.

To sum up, the development of this application fulfils the initial objectives of supervision since the desired functionality was obtained. It allows registering the tank filling. It detects maximum and minimum levels and warns the operator with an alarm to allow him take real time decisions and solve conflictive situations.

6. Recommendations

As future work, it would be important to fully automatize the process to control the level. By doing that, the operator could both fill and empty the tank according to the current need. This would be a great improvement since time and fatigue would be reduced for the operator and hence, money would be saved. In order to do that, an initial investment is required to change the water pump and the filling and emptying valves.

Apart from that, to improve the SCADA it would be advisable to include Visual Basic options, which improve a lot the visibility of the interface and which would allow for example to create a window to display datasheets. Besides, with an internet connection a remote supervision could be possible. This would allow an operator to connect everywhere to monitor the process, or send him an e-mail or a sms to the mobile phone whenever an alarm appears.

Another improvement would be the implementation of a database with the purpose of saving the register of levels and alarms to study trends and correct repetitive errors.

Finally, the sensor with its amplifying circuit should be built on a PCB or even make it waterproof and convert it into a submersible depth sensor with no need of a hose with a weight on the tip to introduce it in the pipe.

:

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8. Appendices

- Appendix I: Pi9911 Level Sensor Datasheet
- Appendix II: SSCSANN005PGAA3 Pressure Sensor Datasheet
- Appendix III: LM741CN Opamp Datasheet

5:1 Turndown Ø30mm
Field Rangeable Submersible

DEPTH SENSOR

Pi9911
Series

- **Depth Ranges 150mmWG to 200mWG**
- **Sealed to IP68 (200mWG)**
- **Robust Construction**
- **Field Adjustable (5:1 turndown)**
- **Lightning (Surge) Protection to EN61000-4-5**
- **Excellent Long Term Stability**
- **Temperature Compensated**
- **Outstanding Performance**
- **3 YEAR WARRANTY**

Options Available

Special Ranging (consult factory)

Extended Temperature Ranges

Different Cable Length

DESCRIPTION

The Pi9911 submersible 2-wire 4-20mA Depth Sensor offers great flexibility with its two piece body design providing ease of access to the 5:1 turndown facility DIL switches and zero & span potentiometers.

Manufactured from 403 Stainless Steel, these two halves are held together using a locking ring and are sealed by means of an 'O' ring arrangement. This, in conjunction with an IP68 sealed polyurethane cable outlet, completes a high integrity waterproof assembly which is rated to 200 metres depth.

Both sensor and electronics are protected against the effects of surges created by lightning strikes, offering distinct advantages over competitive products. The Pi9911 offers rugged construction, excellent long term stability and performance. To further support our claim of long term reliability we offer the product as standard with a 3 Year Warranty.

Transducer Specialists...

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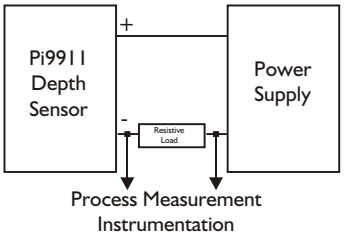
SPECIFICATION

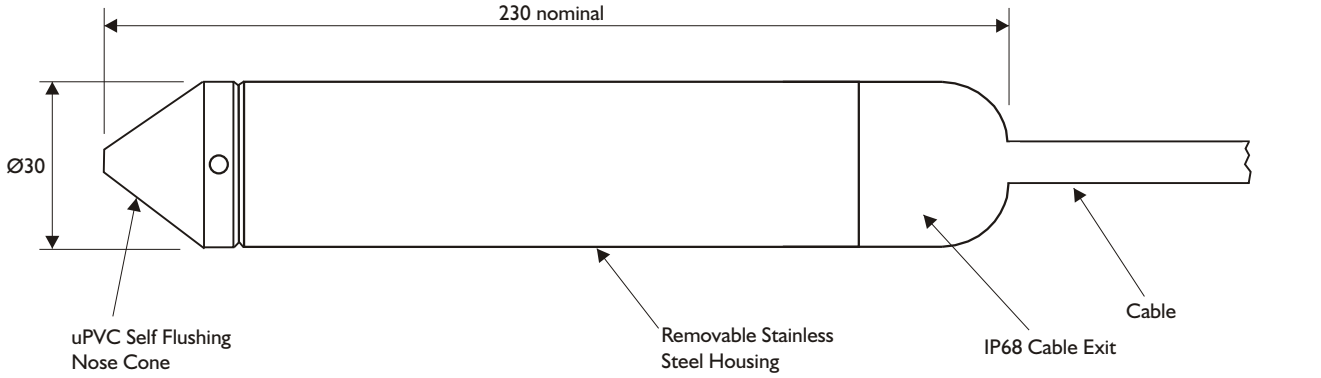
Wiring Schematic Diagram



CHARACTERISTICS		Pi9911	UNITS
Pressure Ranges:		0.15, 0.5, 1, 2, 5, 10, 20, 50, 100, 200*	Metres Water Gauge (mWG)
Safe Overpressure:		150	%Pressure Range
Burst Pressure:		300	%Pressure Range
Supply Voltage:		12- 30	Volts DC
Load Driving Capacity:		1000	Ohms at Max. Supply Voltage
Output Current	Zero Pressure:	4.0	Milliamps (mA)
	Max. Pressure:	20.0	Milliamps (mA)
Electrical Connections:		4-core screened polyurethane sheathed cable with vent tube plus strain and drain wires	
Accuracy:		<0.25	±%Pressure Range
Temperature Range	Operating:	-40 to +80	°C
	Compensated:	0 to +70	°C
Temperature Effect	On Output:	<0.01	±%Pressure Range/°C
	On Zero:	<0.015	±%Applied Pressure/°C
Environmental Protection:		IP68 to 200mWG	
Weight		600 (not including cable)	grams
Construction:		403 St. Steel body with 316 St. Steel Sensing Diaphragm	

*Interim ranges are available if required

All dimensions in mm



Ordering Information

The product part number is coded to assist with ordering, as follows:

e.g.. Pi9911 - 5mWG - C10 - T

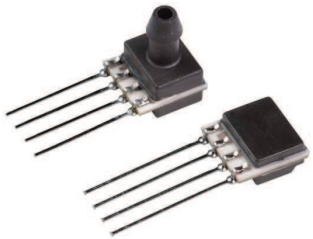
- **Pi9911** Product series type (4-20mA output)
- **5mWG** Range to be set for normal use
- **C10** Cable length in metres - i.e. 10 metres
- **T** Optional ¼" BSPP female thread for tapping to pipe. (A nose cone is supplied as standard)

Continuous product development may result in minor changes to published specifications.

Honeywell

TruStability™ Silicon Pressure Sensors: SSC Series – Standard Accuracy

±2 % Total Error Band, Analog Output, SIP, 1 psi to 150 psi



DESCRIPTION

The TruStability™ Standard Accuracy Silicon Ceramic (SSC) Series is a piezoresistive silicon pressure sensor offering a ratiometric analog output for reading pressure over the specified full scale pressure span and temperature range.

The SSC Series is fully calibrated and temperature compensated for sensor offset, sensitivity, temperature effects, and non-linearity using an on-board Application Specific Integrated Circuit (ASIC). Calibrated output values for pressure are updated at approximately 1 kHz.

The SSC Series is calibrated over the temperature range of -20 °C to 85 °C [-4 °F to 185 °F]. The sensor is characterized for operation from a single power supply of either 3.3 Vdc or 5.0 Vdc.

These sensors measure absolute, differential, and gage pressures. The absolute versions have an internal vacuum reference and an output value proportional to absolute pressure. Differential versions allow application of pressure to either side of the sensing diaphragm. Gage and compound versions are referenced to atmospheric pressure and provide an output proportional to pressure variations from atmosphere.

The SSC Series sensors are intended for use with non-corrosive, non-ionic working fluids such as air and dry gases. They are designed and manufactured according to standards in ISO 9001.

FEATURES

- Industry-leading long-term stability
- Extremely tight accuracy of ±0.25 % FSS BFSL*
- Total error band of ±2 % full scale span maximum
- Modular and flexible design offer customers a variety of package styles and options, all with the same industry-leading performance specifications
- Miniature 10 mm x 10 mm [0.39 in x 0.39 in] package
- Low operating voltage
- Extremely low power consumption
- Ratiometric 12-bit analog output
- Precision ASIC conditioning and temperature compensated over -20 °C to 85 °C [-4 °F to 185 °F] temperature range
- RoHS compliant
- Virtually insensitive to mounting orientation
- Internal diagnostic functions increase system reliability
- Also available with I²C and SPI digital output, and in SMT and DIP packages
- Absolute, differential, gage and compound types
- Pressure ranges from 1 psi to 150 psi (60 mbar to 10 bar)
- Custom calibration available
- Various pressure port options

* Full Scale Span Best Fit Straight Line

POTENTIAL APPLICATIONS

- **Medical:**
  - Airflow monitors
  - Anesthesia machines
  - Blood analysis machines
  - Gas chromatography
  - Gas flow instrumentation
  - Kidney dialysis machines
  - Oxygen concentrators
  - Pneumatic controls
  - Respiratory machines
  - Sleep apnea equipment
  - Ventilators
- **Industrial:**
  - Barometry
  - Flow calibrators
  - Gas chromatography
  - Gas flow instrumentation
  - HVAC
  - Life sciences
  - Pneumatic controls

Table 1. Absolute Maximum Ratings[1]

Parameter	Min.	Max.	Unit
Supply voltage (V_{supply})	-0.3	6.0	V
Voltage on any pin	-0.3	V_{supply} + 0.3	V
ESD susceptibility (human body model)	3	-	kV
Storage temperature	-40 [-40]	85 [185]	° C [° F]
Lead temperature (2 s to 4 s)	-	250 [482]	° C [° F]

Table 2. Operating Specifications

Parameter	Min.	Typ.	Max.	Unit
Supply voltage (V_{supply})[2] 3.3 V 5.0 V *Sensors are either 3.3 or 5.0 V based on model selected*	 3.0 4.75	 3.3[3] 5.0[3]	 3.3 5.25	Vdc
Supply current 3.3 V supply 5.0 V supply	 - -	 1.6 2	 2.1 3	mA
Compensated temperature range[4]	-20 [-4]	-	85 [185]	° C [° F]
Operating temperature range[5]	-40 [-40]	-	85 [185]	° C [° F]
Startup time (power up to data ready)	-	-	5	ms
Response time	-	1	-	ms
Upper output clipping limit	-	-	97.5	% V_{supply}
Lower output clipping limit	2.5	-	-	% V_{supply}
Accuracy[6]	-	-	±0.25	%FSS BFSL
Total error band[7]	-	-	±2	%FSS[8]
Output resolution	12	-	-	bits

Table 3. Environmental Specifications

Parameter	Characteristic
Humidity	0 % to 95 % RH, non-condensing
Vibration	MIL-STD-202F, Curve AK (20.7 g random)
Shock	MIL-STD-202F, Method 213B, Condition F
Life[9]	1 million cycles minimum

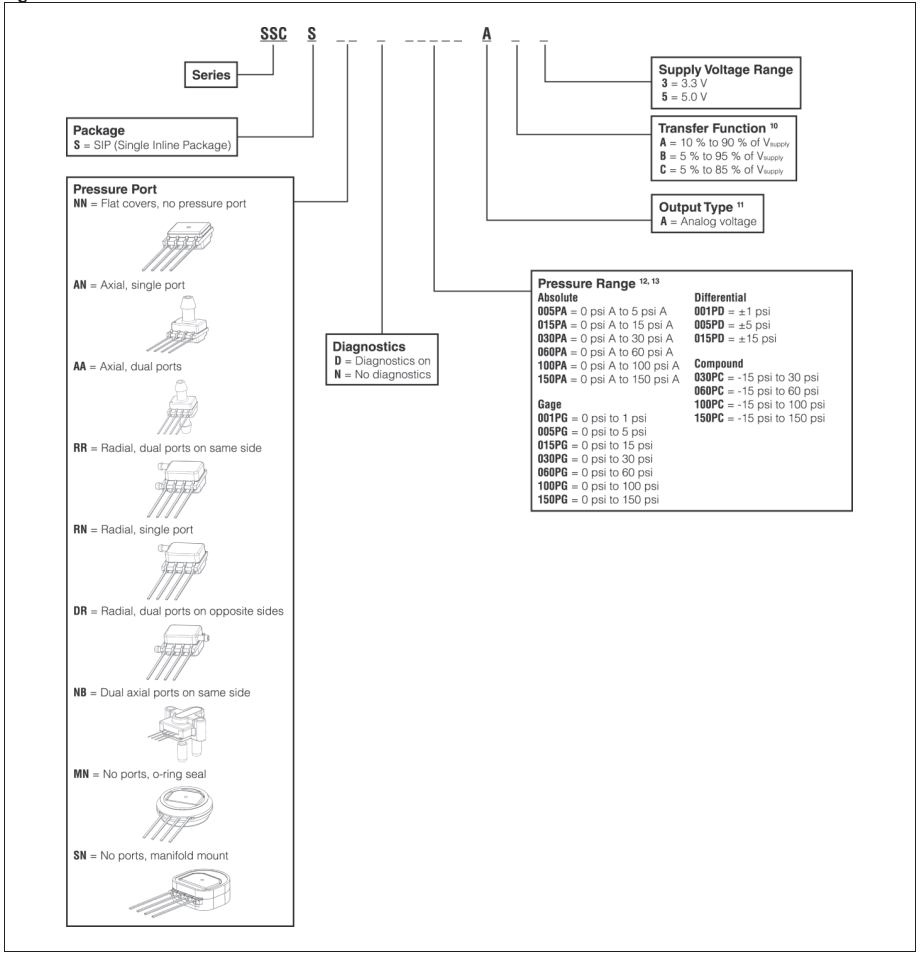
Table 4. Wetted Materials[10]

Parameter	Port 1 (Pressure Port)	Port 2 (Reference Port)
Covers	high temperature polyamide	high temperature polyamide
Substrate	alumina ceramic	alumina ceramic
Adhesives	epoxy, RTV	epoxy, RTV
Electronic components	ceramic, glass, solder, silicon	silicon, glass, gold, solder

Notes:

1. Absolute maximum ratings are the extreme limits the device will withstand without damage.
2. Ratiometricity of the sensor (the ability of the device to scale to the supply voltage) is achieved within the specified operating voltage for each option. Other custom supply voltages are available, please contact Honeywell Customer Service.
3. The sensor is not reverse polarity protected. Incorrect application of supply voltage or ground to the wrong pin may cause electrical failure.
4. The compensated temperature range is the temperature range over which the sensor will produce an output proportional to pressure within the specified performance limits.
5. The operating temperature range is the temperature range over which the sensor will produce an output proportional to pressure but may not remain within the specified performance limits.
6. Accuracy: The maximum deviation in output from a Best Fit Straight Line (BFSL) fitted to the output measured over the pressure range at 25 °C [77 °F]. Includes all errors due to pressure non-linearity, pressure hysteresis, and non-repeatability.
7. Total Error Band: The maximum deviation from the ideal transfer function over the entire compensated temperature and pressure range. Includes all errors due to offset, full scale span, pressure non-linearity, pressure hysteresis, repeatability, thermal effect on offset, thermal effect on span, and thermal hysteresis.
8. Full Scale Span (FSS) is the algebraic difference between the output signal measured at the maximum (P_{max}) and minimum (P_{min}) limits of the pressure range. (See figure 1 for ranges).
9. Life may vary depending on specific application in which sensor is utilized.
10. Contact Honeywell Customer Service for detailed material information.

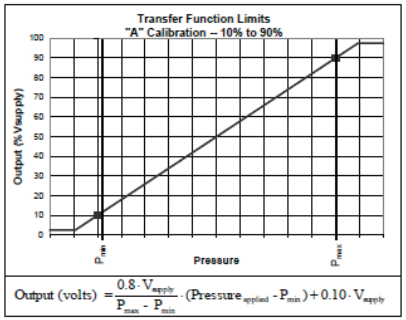
Figure 1. Nomenclature and Order Guide

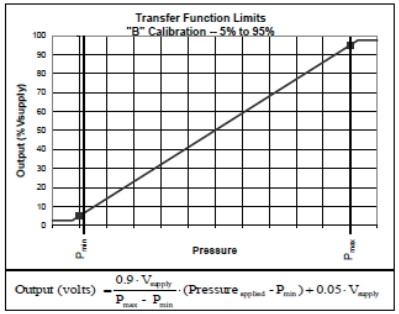

SSC S _ _ _ _ _ _ _ A _ _ _
Series
Package
S = SIP (Single Inline Package)
Pressure Port
NN = Flat covers, no pressure port
AN = Axial, single port
AA = Axial, dual ports
RR = Radial, dual ports on same side
RN = Radial, single port
DR = Radial, dual ports on opposite sides
NB = Dual axial ports on same side
MN = No ports, o-ring seal
SN = No ports, manifold mount
Diagnostics
D = Diagnostics on
N = No diagnostics
Pressure Range 12, 13
Absolute
005PA = 0 psi A to 5 psi A
015PA = 0 psi A to 15 psi A
030PA = 0 psi A to 30 psi A
060PA = 0 psi A to 60 psi A
100PA = 0 psi A to 100 psi A
150PA = 0 psi A to 150 psi A
Gage
001PG = 0 psi to 1 psi
005PG = 0 psi to 5 psi
015PG = 0 psi to 15 psi
030PG = 0 psi to 30 psi
060PG = 0 psi to 60 psi
100PG = 0 psi to 100 psi
150PG = 0 psi to 150 psi
Differential
001PD = ±1 psi
005PD = ±5 psi
015PD = ±15 psi
Compound
030PC = -15 psi to 30 psi
060PC = -15 psi to 60 psi
100PC = -15 psi to 100 psi
150PC = -15 psi to 150 psi
Transfer Function 10
A = 10 % to 90 % of Vsupply
B = 5 % to 95 % of Vsupply
C = 5 % to 85 % of Vsupply
Supply Voltage Range
3 = 3.3 V
5 = 5.0 V
Output Type 11
A = Analog voltage

Notes:

11. The transfer function limits define the output of the sensor at a given pressure input. By specifying P_{min} and P_{max}, the output at P_{min} and P_{max} the complete transfer function of the sensor is defined. See Figure 2 for a graphical representation of the transfer function. Other transfer functions are available. Contact Honeywell Customer Service for more information.
12. Digital outputs (SPI and I²C) are also available. Contact Honeywell Customer Service for more information.
13. Custom pressure ranges are available. Contact Honeywell Customer Service for more information.
14. See Table 5 for an explanation of sensor types.

Figure 2. Transfer Functions and Limits


Transfer Function Limits
"A" Calibration – 10% to 90%
Output (% Vsupply)
Pressure
Output (volts) = 0.8 · Vsupply / (Pmax - Pmin) · (Pressure applied - Pmin) + 0.10 · Vsupply


Transfer Function Limits
"B" Calibration – 5% to 95%
Output (% Vsupply)
Pressure
Output (volts) = 0.9 · Vsupply / (Pmax - Pmin) · (Pressure applied - Pmin) + 0.05 · Vsupply

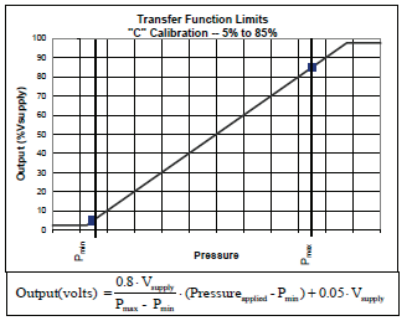
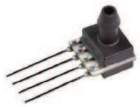

Transfer Function Limits
"C" Calibration – 5% to 85%
Output (% Vsupply)
Pressure
Output(volts) = 0.8 · Vsupply / (Pmax - Pmin) · (Pressure applied - Pmin) + 0.05 · Vsupply

Figure 3. Completed Catalog Listing Example

SSCSANN100PGAA3: SIP, AN ports, no diagnostics, 100 psi gage sensor, 10 % to 90 % calibration at 3.3 V.



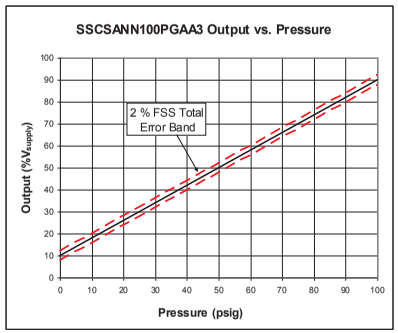


Table 5. Sensor Types

Pressure Type	Description
Absolute	Output is proportional to the difference between applied pressure and a built-in reference to vacuum. P_{min} is set at absolute zero pressure (full vacuum).
Compound	Output is proportional to the difference between applied pressure and atmospheric (ambient) pressure. P_{min} is set at -15 PSI G, referenced to atmospheric pressure.
Differential	Output is proportional to the difference between the pressures applied to each port. (Port1 – Port2) 50% point of transfer function set at Port1 = Port2.
Gage	Output is proportional to the difference between applied pressure and atmospheric (ambient) pressure. P_{min} is set at atmospheric pressure.

Table 6. Pressure Range Specifications

Pressure Range Order Code	Pressure Range		Over-pressure[14]	Burst Pressure[15]	Common Mode Pressure[16]	Long-term Stability (1000 hr, 25 °C [77 °F])
	P_{min}	P_{max}				
Absolute						
005AP	0 psi A	5 psi A	30 psi A	40 psi A	NA	±0.35 %
015AP	0 psi A	15 psi A	30 psi A	60 psi A	NA	±0.25 %
030AP	0 psi A	30 psi A	60 psi A	120 psi A	NA	±0.25 %
060AP	0 psi A	60 psi A	120 psi A	240 psi A	NA	±0.25 %
100AP	0 psi A	100 psi A	250 psi A	250 psi A	NA	±0.25 %
150AP	0 psi A	150 psi A	250 psi A	250 psi A	NA	±0.25 %
Differential						
001PD	-1 psi	1 psi	10 psi	10 psi	150 psi	±0.35 %
005PD	-5 psi	5 psi	30 psi	40 psi	150 psi	±0.35 %
015PD	-15 psi	15 psi	30 psi	60 psi	150 psi	±0.35 %
Gage						
001PG	0 psi	1 psi	10 psi	10 psi	150 psi	±0.35 %
005PG	0 psi	5 psi	30 psi	40 psi	150 psi	±0.35 %
015PG	0 psi	15 psi	30 psi	60 psi	150 psi	±0.35 %
030PG	0 psi	30 psi	60 psi	120 psi	150 psi	±0.35 %
060PG	0 psi	60 psi	120 psi	240 psi	150 psi	±0.35 %
100PG	0 psi	100 psi	250 psi	250 psi	250 psi	±0.35 %
150PG	0 psi	150 psi	250 psi	250 psi	250 psi	±0.25 %
Compound						
030PC	-15 psi	30 psi	60 psi	120 psi	150 psi	±0.25 %
060PC	-15 psi	60 psi	120 psi	240 psi	150 psi	±0.25 %
100PC	-15 psi	100 psi	250 psi	250 psi	250 psi	±0.25 %
150PC	-15 psi	150 psi	250 psi	250 psi	250 psi	±0.25 %

Notes:

15. Overpressure: The maximum pressure which may safely be applied to the product for it to remain in specification once pressure is returned to the operating pressure range. Exposure to higher pressures may cause permanent damage to the product. Unless otherwise specified this applies to all available pressure ports at any temperature with the operating temperature range.
16. Burst pressure: The maximum pressure that may be applied to any port of the product without causing escape of pressure media. Product should not be expected to function after exposure to any pressure beyond the burst pressure.
17. Common mode pressure: The maximum pressure that can be applied simultaneously to both ports of a differential pressure sensor without causing changes in specified performance.

Table 7. Pinout for All Port Styles

Output Type	Pin 1	Pin 2	Pin 3	Pin 4
Analog	NC	V_{supply}	output	ground

Figure 4. Package Dimensional Drawings
(For reference only: mm [in])
(Other package combinations are possible, please contact Honeywell Customer Service.)

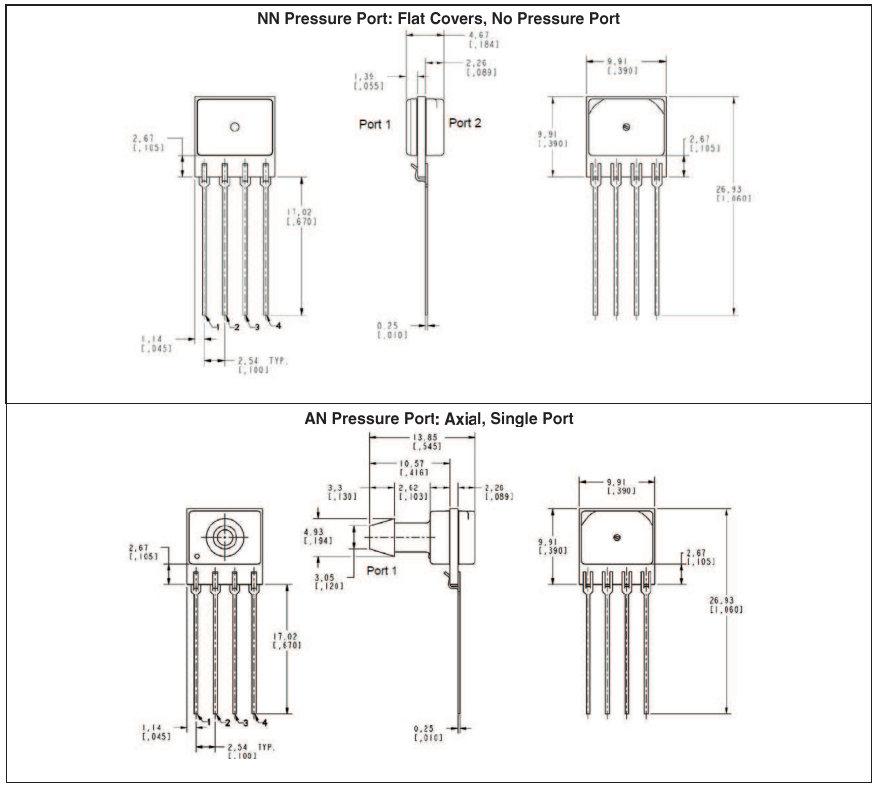


Figure 4. Package Dimensional Drawings (continued)

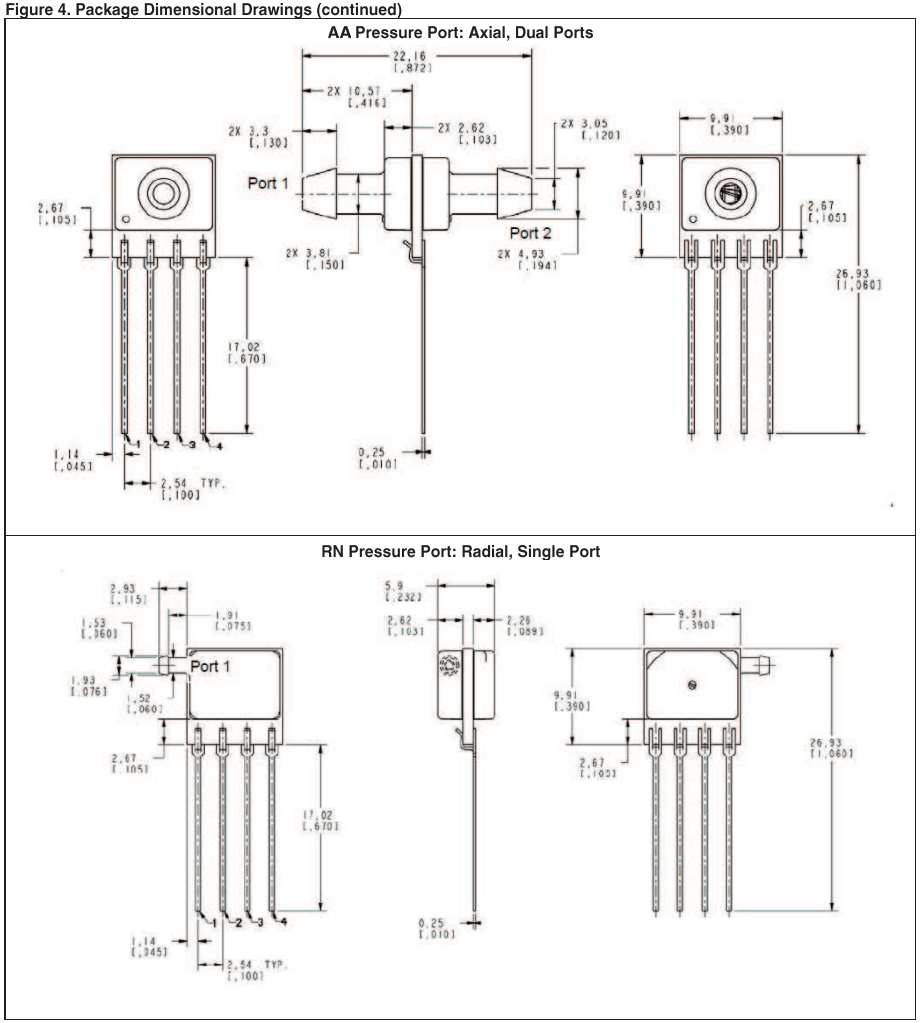
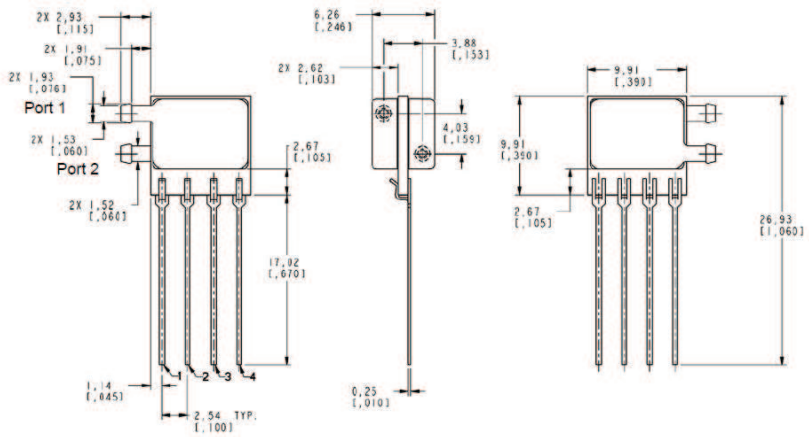


Figure 4. Package Dimensional Drawings (continued)

RR Pressure Port: Radial, Dual Ports on Same Side



DR Pressure Port: Radial, Dual Ports on Opposite Sides

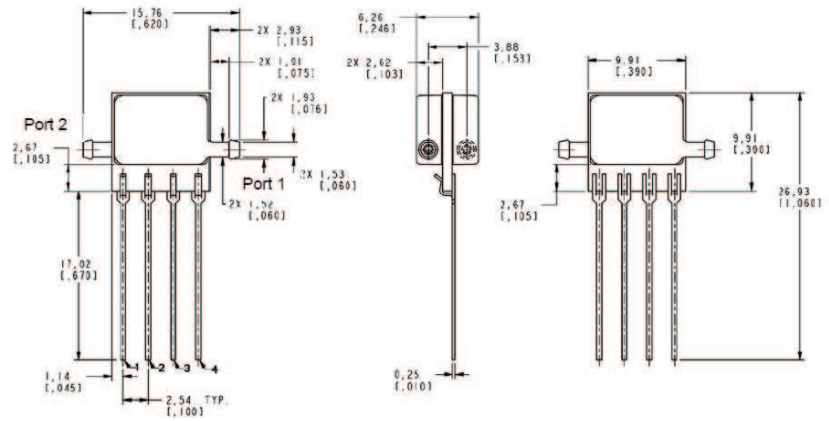
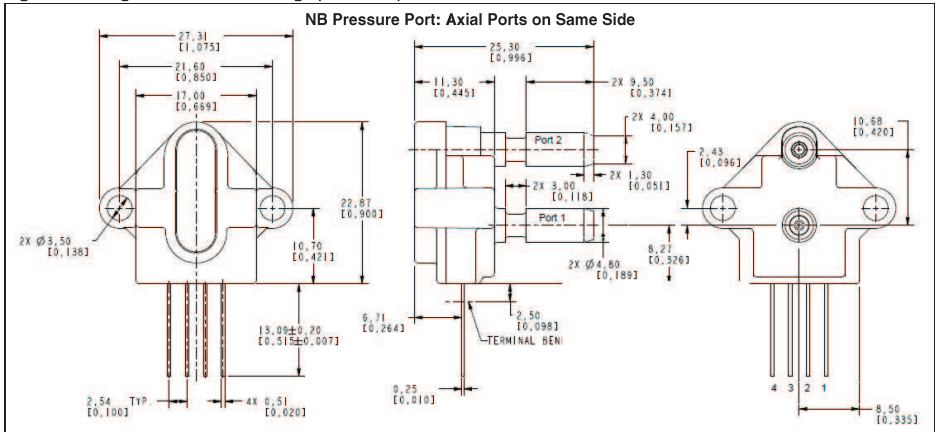


Figure 4. Package Dimensional Drawings (continued)

NB Pressure Port: Axial Ports on Same Side



MN Pressure Port: No Ports, O-Ring Mount

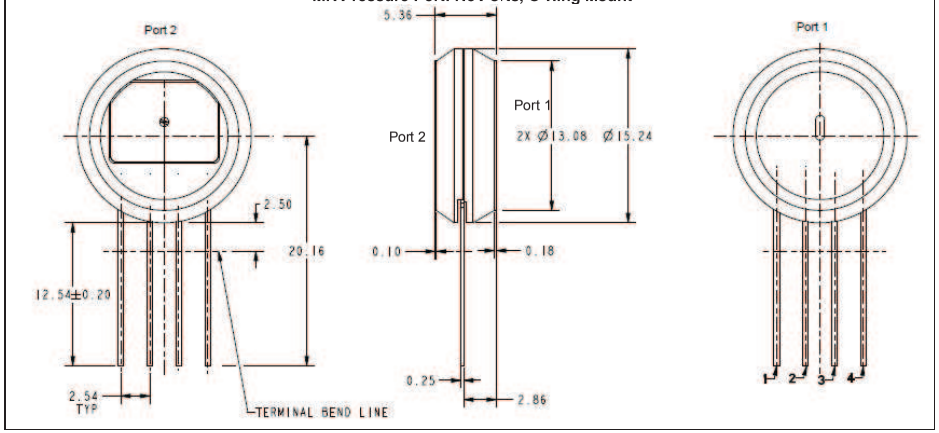
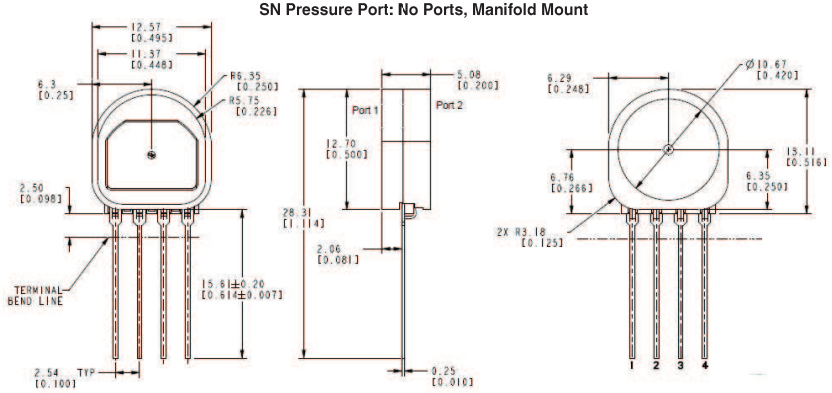


Figure 4. Package Dimensional Drawings (continued)

SN Pressure Port: No Ports, Manifold Mount



⚠ WARNING

PERSONAL INJURY

DO NOT USE these products as safety or emergency stop devices or in any other application where failure of the product could result in personal injury.

Failure to comply with these instructions could result in death or serious injury.

WARRANTY/REMEDY

Honeywell warrants goods of its manufacture as being free of defective materials and faulty workmanship. Honeywell's standard product warranty applies unless agreed to otherwise by Honeywell in writing; please refer to your order acknowledgement or consult your local sales office for specific warranty details. If warranted goods are returned to Honeywell during the period of coverage, Honeywell will repair or replace, at its option, without charge those items it finds defective. **The foregoing is buyer's sole remedy and is in lieu of all other warranties, expressed or implied, including those of merchantability and fitness for a particular purpose. In no event shall Honeywell be liable for consequential, special, or indirect damages.**

While we provide application assistance personally, through our literature and the Honeywell web site, it is up to the customer to determine the suitability of the product in the application.

Specifications may change without notice. The information we supply is believed to be accurate and reliable as of this printing. However, we assume no responsibility for its use.

⚠ WARNING

MISUSE OF DOCUMENTATION

- The information presented in this product sheet is for reference only. Do not use this document as a product installation guide.
- Complete installation, operation, and maintenance information is provided in the instructions supplied with each product.

Failure to comply with these instructions could result in death or serious injury.

SALES AND SERVICE

Honeywell serves its customers through a worldwide network of sales offices, representatives and distributors. For application assistance, current specifications, pricing or name of the nearest Authorized Distributor, contact your local sales office or:

E-mail: info.sc@honeywell.com

Internet: www.honeywell.com/sensing

Phone and Fax:

Asia Pacific	+65 6355-2828; +65 6445-3033 Fax
Europe	+44 (0) 1698 481481; +44 (0) 1698 481676 Fax
Latin America	+1-305-805-8188; +1-305-883-8257 Fax
USA/Canada	+1-800-537-6945; +1-815-235-6847 +1-815-235-6545 Fax

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National Semiconductor

August 2000

LM741
Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

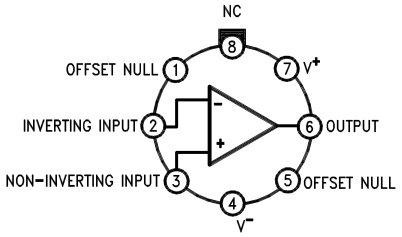
The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0˚C to +70˚C temperature range, instead of −55˚C to +125˚C.

Features

Connection Diagrams

Metal Can Package

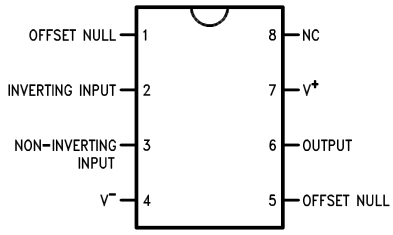


00934102

Note 1: LM741H is available per JM38510/10101

Order Number LM741H, LM741H/883 (Note 1)**, LM741AH/883 or LM741CH**
See NS Package Number H08C

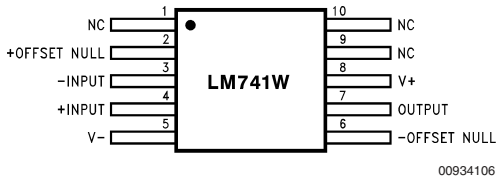
Dual-In-Line or S.O. Package



00934103

Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E

Ceramic Flatpak

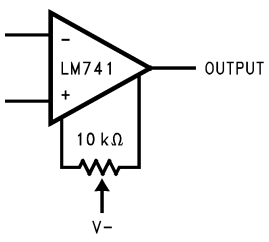


00934106

Order Number LM741W/883
See NS Package Number W10A

Typical Application

Offset Nulling Circuit



00934107

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Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55˚C to +125˚C	−55˚C to +125˚C	0˚C to +70˚C
Storage Temperature Range	−65˚C to +150˚C	−65˚C to +150˚C	−65˚C to +150˚C
Junction Temperature	150˚C	150˚C	100˚C
Soldering Information			
N-Package (10 seconds)	260˚C	260˚C	260˚C
J- or H-Package (10 seconds)	300˚C	300˚C	300˚C
M-Package			
Vapor Phase (60 seconds)	215˚C	215˚C	215˚C
Infrared (15 seconds)	215˚C	215˚C	215˚C
See AN-450 “Surface Mounting Methods and Their Effect on Product Reliability” for other methods of soldering surface mount devices.			
ESD Tolerance (Note 8)	400V	400V	400V

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25˚C$										
	$R_S \le 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \le 50\Omega$		0.8	3.0							mV
	$T_{AMIN} \le T_A \le T_{AMAX}$										
	$R_S \le 50\Omega$			4.0							mV
	$R_S \le 10\ k\Omega$						6.0			7.5	mV
Average Input Offset Voltage Drift				15							µV/˚C
Input Offset Voltage Adjustment Range	$T_A = 25˚C$, $V_S = \pm 20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25˚C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/˚C
Input Bias Current	$T_A = 25˚C$		30	80		80	500		80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			0.210			1.5			0.8	µA
Input Resistance	$T_A = 25˚C$, $V_S = \pm 20V$	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, $V_S = \pm 20V$	0.5									MΩ
Input Voltage Range	$T_A = 25˚C$							±12	±13		V
	$T_{AMIN} \le T_A \le T_{AMAX}$				±12	±13					V

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Large Signal Voltage Gain	$T_A = 25^\circ C$, $R_L \geq 2\ k\Omega$										
	$V_S = \pm 20V$, $V_O = \pm 15V$	50									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				50	200		20	200		V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
	$R_L \geq 2\ k\Omega$,										
	$V_S = \pm 20V$, $V_O = \pm 15V$	32									V/mV
	$V_S = \pm 15V$, $V_O = \pm 10V$				25			15			V/mV
	$V_S = \pm 5V$, $V_O = \pm 2V$	10									V/mV
Output Voltage Swing	$V_S = \pm 20V$										
	$R_L \geq 10\ k\Omega$	±16									V
	$R_L \geq 2\ k\Omega$	±15									V
	$V_S = \pm 15V$										
	$R_L \geq 10\ k\Omega$				±12	±14		±12	±14		V
	$R_L \geq 2\ k\Omega$				±10	±13		±10	±13		V
Output Short Circuit	$T_A = 25^\circ C$	10	25	35		25			25		mA
Current	$T_{AMIN} \leq T_A \leq T_{AMAX}$	10		40							mA
Common-Mode	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
Rejection Ratio	$R_S \leq 10\ k\Omega$, $V_{CM} = \pm 12V$				70	90		70	90		dB
	$R_S \leq 50\Omega$, $V_{CM} = \pm 12V$	80	95								dB
Supply Voltage Rejection	$T_{AMIN} \leq T_A \leq T_{AMAX}$,										
Ratio	$V_S = \pm 20V$ to $V_S = \pm 5V$										
	$R_S \leq 50\Omega$	86	96								dB
	$R_S \leq 10\ k\Omega$				77	96		77	96		dB
Transient Response	$T_A = 25^\circ C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		µs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	$T_A = 25^\circ C$	0.437	1.5								MHz
Slew Rate	$T_A = 25^\circ C$, Unity Gain	0.3	0.7			0.5			0.5		V/µs
Supply Current	$T_A = 25^\circ C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25^\circ C$										
	$V_S = \pm 20V$		80	150							mW
	$V_S = \pm 15V$					50	85		50	85	mW
LM741A	$V_S = \pm 20V$										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	$V_S = \pm 15V$										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Electrical Characteristics (Note 5) (Continued)

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100˚C/W	100˚C/W	170˚C/W	195˚C/W
θ_{jC} (Junction to Case)	N/A	N/A	25˚C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

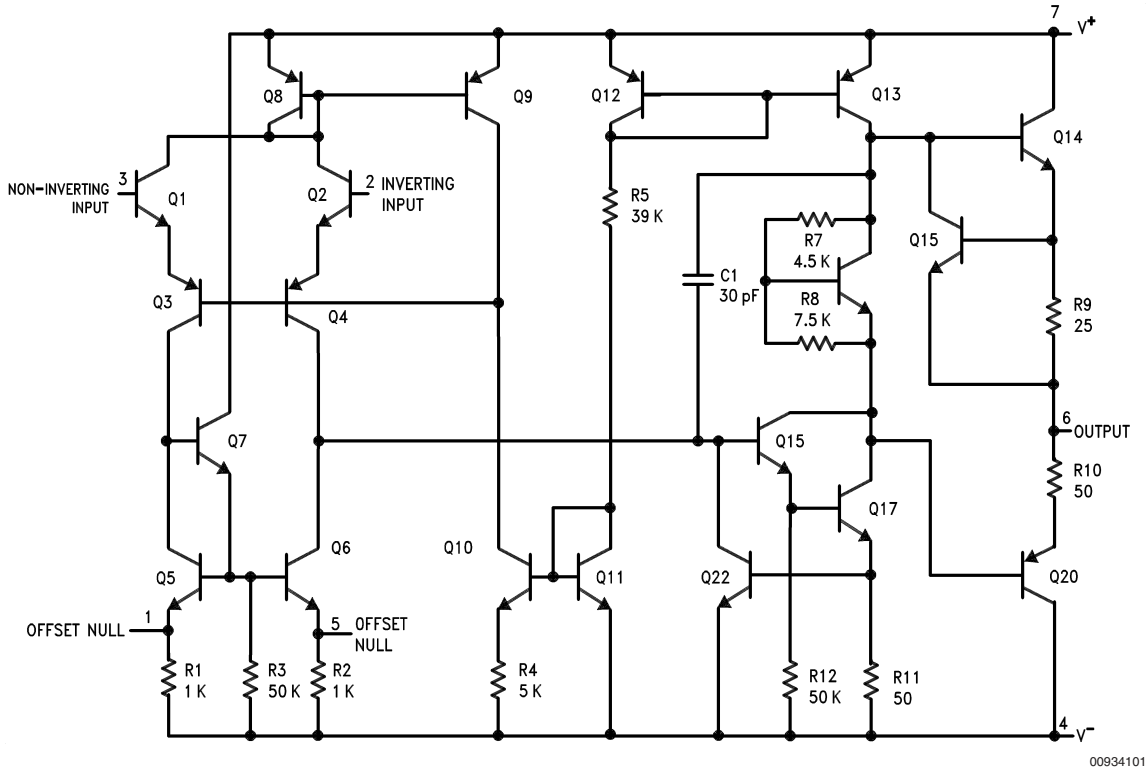
Note 5: Unless otherwise specified, these specifications apply for V_S = ±15V, −55˚C ≤ T_A ≤ +125˚C (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to 0˚C ≤ T_A ≤ +70˚C.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(μs).

Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

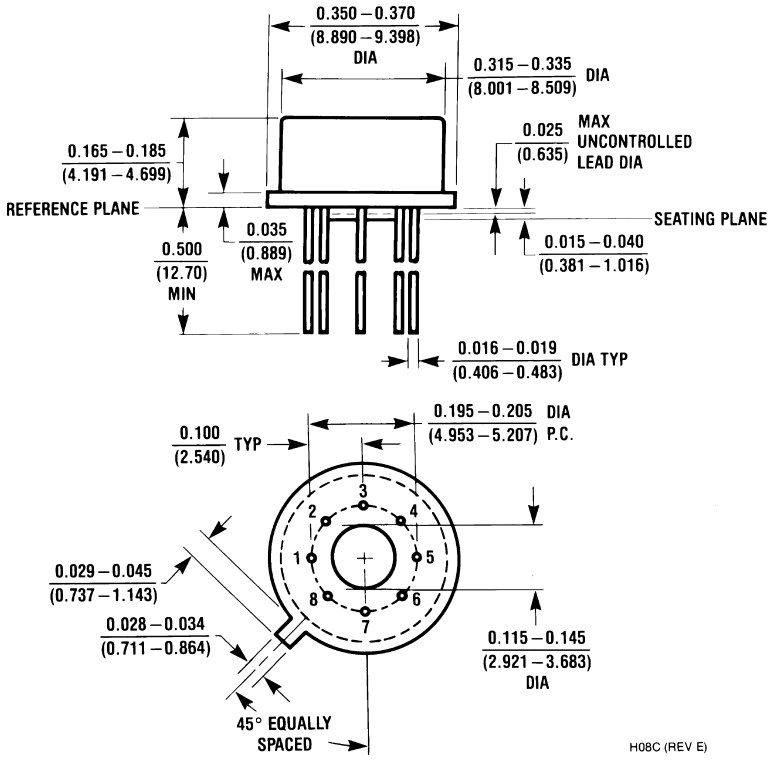
Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram



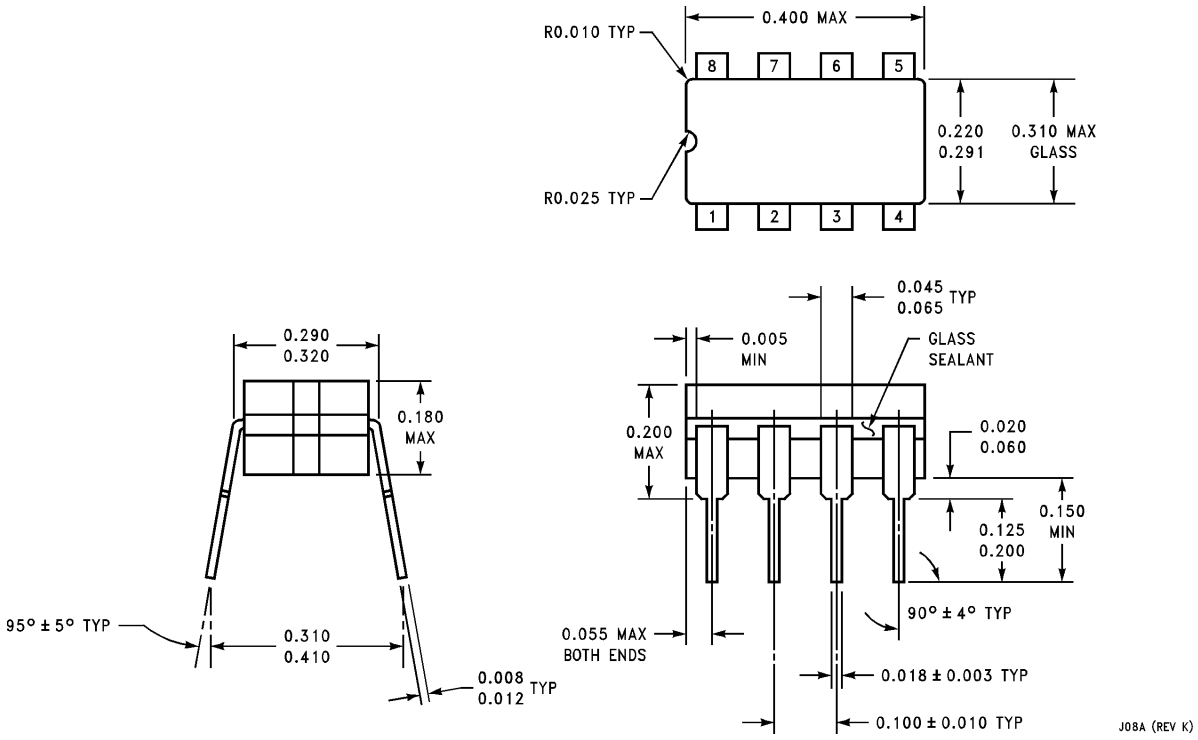
Physical Dimensions inches (millimeters)

unless otherwise noted

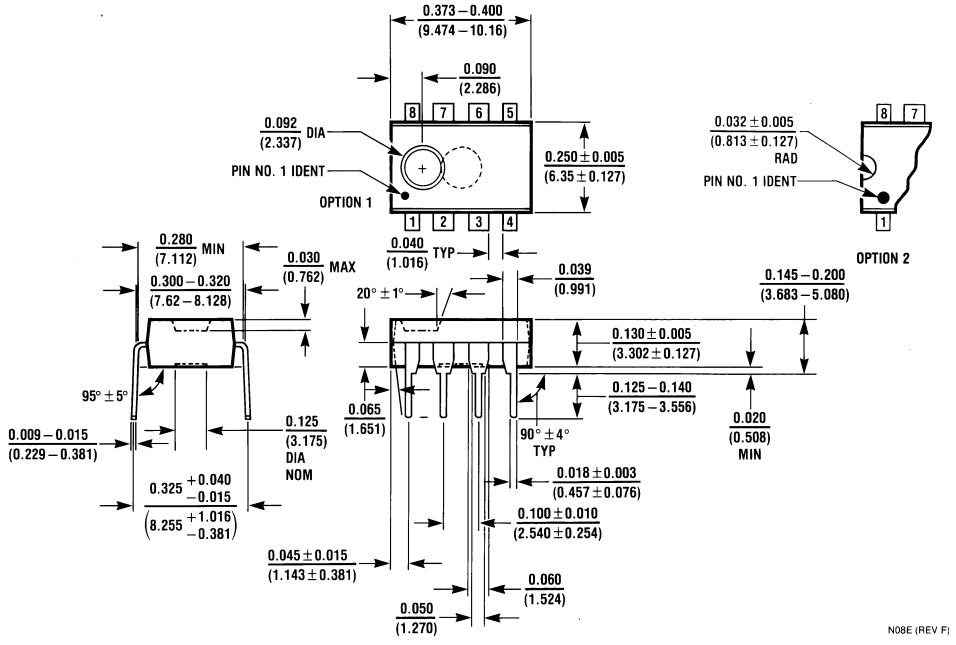


Metal Can Package (H)
Order Number LM741H, LM741H/883, LM741AH/883, LM741AH-MIL or LM741CH
NS Package Number H08C

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)

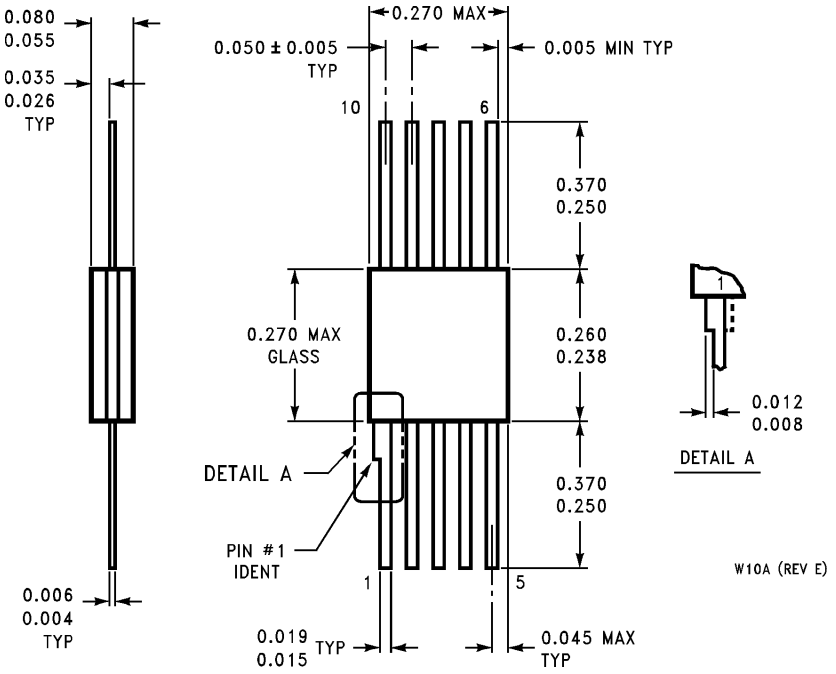


Ceramic Dual-In-Line Package (J)
Order Number LM741J/883
NS Package Number J08A



Dual-In-Line Package (N)
Order Number LM741CN
NS Package Number N08E

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



10-Lead Ceramic Flatpak (W)
Order Number LM741W/883, LM741WG-MPR or LM741WG/883
NS Package Number W10A

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